AFT Impulse™

Verification Cases

AFT Impulse Version 9

Waterhammer Modeling in Piping Systems

Published: May 01, 2023



Dynamic solutions for a fluid world ™

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AFT Impulse Verification Overview

There are a number of aspects to the verification process employed by Applied Flow Technology to ensure that AFT Impulse provides accurate solutions to waterhammer and surge transient problems in pipe flow systems. These are discussed in <u>Verification Methodology</u>. A listing of all of the verified models is given in <u>Summary of Verification Models</u>. The verification models are taken from numerous <u>References</u>.

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Verification Reference - Brown Cover Page

R. J. BROWN K. J. B... General Engineer, Technical Engineering Analysis Branch, Bureau of Reclamotion, Denver, Colo.

Water-Column Separation at **Two Pumping Plants**

Results of field measurement of transients in two pump discharge lines show that the pressures were greater than had been predicted during design, and a theory and method of analysis are developed which explains the time-history of the transients measured. The field measurements were undertaken because of the complexity of the phenomena and because every little measured data were available. Results are presented graphically of prediction of water-column separation effects is further complicate by the uncertainty about complete pump operating characteristics and actual moment of inertia of pumps and motors; (b) the effects of air and gaess entrained in solution in the water-meantal effect on the water-hammer transient, i.e., larger pressure surges in the discharge line and higher reverse speeds of the pumps can be caused by its presence.

Introduction

An important consideration in the design of a pump discharge line is the possible occurrence of water-column separa-tion during a water-hammer transient. Following a power out-age at the pumping units, negative pressure wares of the tion during a water-hammer transient. Following a power out-age at the pumping units, negative pressure aves will be propagated throughout the discharge line. Water-column sepa-ration will appear when the transient hydraulic gradient drops to the vapor pressure of water at any point in the line. These phenomena can be visualized as two individual water columns separated by a vapor pocket at the low pressure point. In gen-eral, the water-hammer pressure created when the two liquid water columns rejoin is of a destructive nature, being very large in memiuted. in magnitude.

in magnitude. In 1946, the Bureau of Reclamation designed Mile 7.2 and Mile 22.5 Pumping Plants [1]¹ with the knowledge that water-column separation would occur during operation of the systems. These pumping plants were selected as ideal trial cases because

¹ Numbers in brackets designate References at end of paper. Contributed by the Fluids Engineering Division and presented at the Fluids Engineering Conference, Philadelphia, Pa., May 6-9, 1968, of The AvernerAN SOCIETY or MUCRANCEAL ENGINEERING Manuscript received at ASME Headquarters, February 13, 1908. Paper No. 69-FE/23.

-Nomenclature-

A = cross-sectional area of the pipe-

- line, ft2 a = velocity of pressure wave, ft/sec
- C = total volume of air and entrainedgases, at an absolute pressure head of 34 ft, in the discharge line, ft²
- \bar{C} = air volume/inner volume of dis-charge pipe
- C_i = air volume at gas pocket at loca-tion *i*, ft³
- D = inside diameter of pipeline, ft
- f = Darcy's friction factor
- H = head between hydraulic grade line and forebay elevation, ft

 $H_0 =$ head across the unit, ft

Invent of Dasis Ensinearing

Q = discharge at a point in the pipe- H_{Li} = head from forebay elevation to absolute zero pressure head level for the gas at location line, cfs Q_{B} = rated discharge, cfs

The original beside in the sustained and the set of the

both of the discharge lines had distinct "knees" in their profiles, and, therefore, the exact locations of the points of separation were predetermined. Water-column separation is a complicated phenomenon and after the pumping plants were built, the ac-curacy and completeness of the theory used to predict the tran-

curacy and completeness of the theory used to predict the tran-sient pressures were questioned. To check the theoretical approach, field tests were performed and pressure-time histories were recorded at various test sta-tions on the line. In general, the measured transient pressures were greater than had been predicted. In the following sections, the original design for water-column separation in the pump discharge lines will be reviewed. The results of the recorded pressure-time histories from the field tests will be explained and presented in graphical forms. A modified theoretical approach devised to more accurately pre-dict the phenomena will be discussed.

Original Design Criteria

i, ft H_{ui} = head from forebay elevation to

 $\begin{array}{l} H_{R} \\ L = \operatorname{length} \operatorname{of} \operatorname{discharge line, ft} \\ L_{i} = \operatorname{length} \operatorname{of} \operatorname{line between gas pocket} \\ \operatorname{locations, ft} \\ N = \operatorname{speed} \operatorname{of} \operatorname{unit, rpm} \\ N_{R} = \operatorname{rated} \operatorname{speed} \operatorname{of} \operatorname{unit, rpm} \\ N_{s} = \operatorname{specific speed} \operatorname{of} \operatorname{unit, gpm} \operatorname{units} \end{array}$

 $\begin{array}{l} \text{nead revel at gas}\\ \text{tion } i, \text{ ft} \\ H_P = \text{pumping head, ft} \\ H_R = \text{ rated head, ft} \end{array}$

 $h = \frac{H_p}{H_R}$

an upper effective pressure head level at gas pocket loca-

- q = discharge/rated discharge T = torque on the unit, lb-ft
- l = time, sec $V = \text{velocity at a point in the pipe-$ line, fps

- line, fps $V_R = \operatorname{rated} \operatorname{velocity}, fps$ $v = V/V_R$ $WR^2 = \operatorname{flywheel}$ effect of the rotating parts of the pump and motor, $1b (1^2)$
 - α = speed of unit/rated speed β = torque on unit/rated torque
 - $\rho = \frac{aV_R}{2g H_R} = \text{pipeline constant}$

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Verification Reference - Chaudhry Cover Page



Verification Reference - Kamemura Cover Page

List of All Verification Models

NIPPON KOKAN TECHNICAL REPORT Overseas No. 52 (1988)

Fluid Transients in Pipeline

-Liquid Column Separation and Development of Comprehensive Program-

Toshihiko Kamemura*, Kazuo Jyowo**, Teruhiko Hata***, Hideo Hayashi****, Tatsuki Yoshikai***** and Munetaka Kondo******

NKK has developed a computer program, SURGE 2, to simulate transient phenomena in liquid pipeline. SURGE 2 can analyze any piping systems, however complicated they may be. Furthermore this program can simulate liquid column separation. For numerical analysis, the characteristics method which is introduced air release method is adopted. Liquid column separation experiments were con-ducted using 15.2mm in diameter and 200m long test pipeline. Experimental data were compared with calculated results to find out good agreement in respect to change of flow rate and pressure.

1. Introduction

In planning and designing a pipeline, fluid transi-ents phenomena cause problems of significant engineering concern especially in two aspects. The first problem is the high and low pressure caused by the transients phenomena. High pressure brings about destructive damage to pipes and devices, while low pressure causes cavitation, resulting in various troubles such as breakdown of pumps and others. Liquid column separation phenomenon resulting from low pressure also brings about destructive high pressure with the collapse of vapor cavity. The second prob-lem is the effect of fluid transients phenomena to various control systems and conversely, the effect of control systems to the pipeline system.

In recent years, as a result of active pursuit of safety and total efficiency of plants and pipelines, the piping system is becoming complicated. In a complicated piping system, adverse effects from fluid transi-ents phenomena frequently occur, the effects spreading to many directions. Under these circumstances, in 1974, NKK developed SURGE 1, a computer program to simulate fluid transients phenomena. Since then, SURGE 1 has been applied to analysis of fluid trans-portation in many pipelines and has demonstrated its power. However, SURGE 1 had problems; that it could not analyze liquid column separation phenomenon, influence of trapped air in pipe, and transients phenomena of looped piping. Also, it could not deal with equipment such as surge tanks, air valves and others

Consequently, a comprehensive program. SURGE to analyze the above phenomena was completed in 1986, after three years of development. The feature of SURGE 2 is that it can calculate both the steady and unsteady flow problems of the piping system, however complicated they may be, and also analyze liquid column separation phenomenon. In addition, experiments were conducted on a 15.2mm diameter, 200m length test pipeline, the results of which were compared with analytic results to examine the relia-bility of the program.

In this paper, the analytic theory, function, and experimental verification of SURGE 2 are presented.

2. Analytic theory

2.1 Steady flow calculation

Various reports have been made for solution of steady flow piping network, but in SURGE 2, New-ton-Raphson's solution was adopted in view of its applicability under diverse conditions.

A piping network is modeled with flow paths and joints. Section points, branch and confluence points, and boundary points of piping are treated as the joints, and connecting these joints are the flow paths. A flow path consists of pipes, valves, and pumps.

Generally, the relationship between pressure. P, and the flow rate, Q, are expressed as:

Manager, Pipeline Design Sec., Engineering & Design Dept.
Team Manager, Pipeline Design Sec., Engineering & Design Dept.
Pipeline Design Sec., Engineering & Design Dept.
General Manager, No. I Research Dept., Kawasaki Research Labs., Engineering Research Center
Manager, Information Systems Dept.
Manager, Pipeline Inspection Services

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Verification Reference - Kaplan Cover Page

THE UNIVERSITY OF MICHIGAN INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

OIL PIPELINE TRANSIENTS

Michel Kaplan Victor L. Streeter E. Benjamin Wylie

> August, 1966 IP-743

Verification Reference - Karney Cover Page - Efficient Calculation...

EFFICIENT CALCULATION OF TRANSIENT FLOW IN SIMPLE PIPE NETWORKS

By Bryan W. Karney¹ and Duncan McInnis²

ABSTRACT: Extensions to the conventional method of characteristics allow transient conditions in simple pipe networks to be efficiently calculated. In particular, treating both boundary conditions and network topology in a general and comprehensive fashion simplifies the solution of many combinations of hydraulic devices. The algebraic framework presented includes a flexible integration of the friction loss term that reduces to previous linear approximations as special cases. In addition, an explicit algorithm is derived for a general hydraulic element called an external energy dissipator. This boundary condition conveniently represents surge tanks, telef valves, storage reservoirs, valves discharging to the atmosphere, and many other common devices. Significantly, the solution remains explicit even if friction losses and incrita effects are present in both the storage element and a connecting pipe. This comprehensive approach to transient analysis simplifies control logic, encourages accurate reporting of field data, and improves execution times. The procedure is illustrated by analyzing transient conditions in a small network containing a variety of devices.

INTRODUCTION

Although water distribution networks have existed for hundreds of years, transients have not always been explicitly considered in design calculations. Early networks were fed by gravity from high-elevation reservoirs or water towers, and nearly steady conditions prevailed in the system. In addition, the number, length, and diameter of pipes were typically small and pressures low. The most significant problem was to predict the equilibrium distribution of flow under assumed demand conditions. Thus, the lack of attention given to transient considerations in these networks was usually well-justified.

Modern water distributions in these networks was usually weinjustified. Modern water distribution systems, by contrast, are usually fed by nimerous pumping stations discharging directly into the system. In addition, flow disturbances are common. The automatic stopping of pumps, the adjustment of control valves and the influence of accidential events, such as power outages, all generate transient conditions. These disturbances are superimposed on a network that has large pipes and high discharge rates. The result is a highly dynamic system that should be analyzed as such (Sharp 1981; Karney and McInnis 1990).

This paper is intended to facilitate calculation of transient conditions in pipe networks. Although a general algebraic and conceptual framework applicable to any network is presented, special attention is given to combinations of simple devices. No attempt is made to treat all boundary conditions comprehensively (an impossible task in a single paper). Rather, the purpose is to show how significant gains in efficiency and accuracy can be achieved for a class of boundary conditions called external energy dissipators. An explicit equation is presented for this composite storage element

¹Asst. Prof., Dept. of Civ. Engrg., Univ. of Toronto, MSS 1A4, Canada. ²Grad. Student, Dept. of Civ. Engrg., Univ. of Toronto, Toronto, MSS 1A4, Canada.

Cantada. Note. Discussion open until December 1, 1992. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on May 23, 1990. This paper is part of the *Journal of Hydraulic Engineering*, Vol. 118, No. 7, July, 1992. @ASCE, ISSN 0733-9429/92/0007-1014/\$1.00 + \$.15 per page. Paper No. 26648.

1014

that accounts for losses in a short conduit connecting a reservoir to a j tio of any number of pipes. Such a solution is useful in itself and serves as model for solving more complex boundary conditions. The versatility ar efficiency of the approach are demonstrated by analyzing a small test new work.

GOVERNING EQUATIONS AND THEIR SOLUTION

This section extends the conventional method of characteristics for ne work applications. The key result is a linear equation that accounts for an number of interacting pipes at a network node. Although a similar relation is developed in Wylic and Streeter (1982), the equation developed here algebracially simpler while being computationally more flexible, particular in relation to the linearization of the friction term.

Two equations, a momentum equation and a relation of mass conservation, are used to model transient flow in closed conduits [e.g., Chaudh (1987), Wylie and Streeter (1982)]. If x is distance long the centerline the conduit, t is time, and partial derivatives are represented as subscript these equations can be written as

$$H_t + \frac{a^2}{g}V_x = 0 \qquad (2)$$

in which H = H(x,t) = piezometric head; V = V(x,t) = fluid velocity; L = inside pipe diameter; f_p = Darcy-Weisbach friction factor; a = celeri of the shock wave; and g = acceleration due to gravity. To be compatible x and V must be positive in the same direction. Eqs. (1) and (2) are vali if the flow is one-dimensional, the conduit properties (diameter, wave spect temperature, etc.) are constant, the convective and slope terms are smal and the friction force can be approximated by the Darcy-Weisbach formut for steady flow. In addition, it is usually assumed that the friction factor is either constant or weakly dependent on Reynolds number. The popular method of characteristics (MOC) is a simple and numerical provides the provides the provides the provides the provides the popular method of characteristics (MOC) is a simple and numerical provides the provides

The popular method of characteristics (MOC) is a simple and numerical efficient way of solving the unsteady flow equations (Wylie and Street 1982; Chaudhry 1987). In essence, the MOC combines the momentum at continuity expressions to form the following compatibility equation in di charge Q and head H:

in which $A_p = \text{cross-sectional area of the pipe}$; $B = a/gA_p$; and $R = f_p\Delta 2gD_pA_p^2$. Eq. (3) is valid only along the so-called C^+ and C^- characterist lines defined by $dx/dt = \pm a$. To satisfy these characteristic relations, the x-t grid is usually chosen to ensure $\Delta x = \pm a\Delta t$ (see Fig. 1).

These defined by $dx/dt = \pm d$. To satisfy these characteristic relations, if x-t grid is usually chosen to ensure $\Delta x = \pm a\Delta t$ (see Fig. 1). Once initial conditions and the space-time grid have been specified, (can be integrated along AP and BP in Fig. 1. Although the first two terr are easily computed, the third integral requires the variation of Q with to be known. In practice, the flow component has usually been approximate as either $Q_A |Q_A|$ or $Q_P |Q_A|$ (Wylie 1983; Wylie and Streeter 1982; Chaudh

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Verification Reference - Karney Cover Page - Transient Analysis...

1

Transient Analysis of Water Distribution Systems

Bryan W. Karney and Duncan McInnis

The pressures generated by transient (water hammer) conditions in pipe systems are frequently three or more times the value of normal operating pressures. Thus, transient pressures must be known if the size and strength of the required pipe is to be rationally selected, if surge-suppression equipment is to be logically sized, and if system operating rules are to be intelligently specified. In practice, however, analysts frequently neglect transient conditions, particularly in complex systems such as distribution networks. With modern computer techniques it is possible to analyze distribution systems under a wide range of flow conditions and with relatively few restrictions. Examples are presented of the dangers of oversimplifying either the physical system or the operating conditions.

Pressure pipe systems are subject to a wide range of physical loads and operational requirements. For example, underground piping systems must withstand internal and external corrosion, various forms of bedding stresses, differential settlement, construction damage, local stresses at connections, as well as other external and internal forces. As a result of this ongoing chemical and physical attack, both the hydraulic and

structural capacities of the pipe are reduced over time until some kind of failure occurs. The failure may be physical in nature, such as a break that causes loss of water and pressure, or it may be economic, arising from increased fluid friction with its associated reduced flow capacity, increased power costs, or both. In Canada alone, the estimated cost of repairing water main breaks exceeds Can\$100 million annually.



One source of loading that is commonly neglected in water distribution system analysis is due to water hammer or transient conditions. Although it is well known that the pressures generated during transient conditions should be an important consideration when simple pipeline systems are being designed, there is widespread belief that transient conditions are intrinsically less severe in network applications. In fact, several examples in this article demonstrate that the maximum transient pressure in some branched and looped systems may exceed the corresponding pressure rise

One source of loading commonly neglected in system analysis is due to water hammer or transient conditions.

in a simple system. Thus, if the size and strength of the required pipe are to be rationally selected, if the surge-suppression equipment is to be logically sized, and if system operating rules are to be intelligently specified, reliable transient analysis is essential.

In the past few years, many refinements and improvements have been made in the accuracy and efficiency of transient analysis. More attention, however, has frequently been given to how the analysis is performed than to what is being modeled. Many articles have been written on the relative accuracy and computational merits of various numerical procedures; few have considered the assumed initial state or what kind of interaction between automatic control

JOURNAL AWWA

Verification Reference - Liou Cover Page

Understanding Line Packing in Frictional Water Hammer

Jim C. P. Liou

Mem, ASME Department of Civil Engineering University of Idaho, Moscow, ID 83844-1022 e-mail: liou@uidaho.edu For valve closure transients in pipelines, friction attenuates the amplitude of water ham-mer wave fronts and causes line packing. The latter is a sustained head increase behind the wave front. Line packing can lead to overpressure. Because of the nonlinearity of the friction term in the governing equations of water hammer, a satisfactory analytical explanation of line packing is not available. Although numerical methods can be used to compute the ine packing an analytical explanation is desirable to better understand the phenomenon. This paper explains line packing analytically and presents a formula to compute the line packing take leads to the maximum pressure at the closed valve. [DOI: 10.1115/1.4033368]

Introduction

In pipeline transients, frictional resistance to flow generates line In pipeline transients, includina resistance to now generates line packing, which is a sustained pressure rise in the pipeline behind the water hammer wave front after the closure of a discharge valve. This phenomenon is of interest to cross-country oil pipe-lines and long water transmission mains because the sustained pressure rise can be very significant relative to the initial sudden pressure rise by water hammer and can result in unacceptable verpressures

pressure rise by water hammer and can result in unacceptable overpressures. For a highly frictional pipeline, where the length is large and/or the diameter is small, the effective closure time of a discharge valve is much shorter than its physical closure time [1]. For such pipelines, line packing can be analyzed in terms of an instantane-ous closure of a discharge valve. Figures 1 and 2 contrast the valve closure transients with and without friction. Depicted in Fig. 1 is the water hammer without friction, with H_U = head at the reservoir end, H_V = head at the valve end, V_0 = steady-state discharge velocity. V = velocity immediately behind the wave front, a = wave speed, t = time, and dt = a time increment. The head and velocity profiles at t (solid lines) and t+dt (dotted lines) are indicated. The profiles represent the head and velocity waves of water hammer. The initial hydraulic grade line is horizontal. The head rise at the closed valve progades upstream unattenuated. The velocity behind the head wave is stopped completely. Before the waves are reflected back to the valve, the head at the closed valve remains constant and equals velocity. Devicted in Eig 2 is the water hammer with friction [In this fig. velocity.

Depicted in Fig. 2 is the water hammer with friction. In this fig-Depicted in Fig. 2 is the water nammer with intensity $u_{\rm res}$, $L = {\rm pipe}$ length and $x = {\rm distance measured from the reservoir toward the valve. The head wave attenuates as it travels upstream. The velocity is not stopped fully by passage of the head wave. There is a sustained head rise behind the wave front as more and more fluid is packed into the closed end. If the wave front is sufficiently attenuated, the head at the closed valve will rise over time$ Compared and the near at the close of size with the over time almost monotonically toward H_U . If the attenuation is less, the head wave reflected from the reservoir will reverse the head rise at the closed valve 2L/a s after the valve closure. For the latter case, the peak head at the closed end at 2L/a s may significantly exceed H_U. This peak pressure, hereafter referred to as line pack-ing, is addressed in this paper. In fluid mechanics and hydraulics textbooks that discuss water hammer, the friction effect is either not addressed or only briefly

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Verification Reference - Parmakian Cover Page

List of All Verification Models

mentioned about the extent of its damping effect [2,3, for exam-ple]. To the knowledge of the author, the only exception is Ref. ple]. To the knowledge of the author, the only exception is Ref. [4], which gives an approximation formula for line packing. Phe-nomenological explanations of attenuation and line packing are found in textbooks on water hammer [5,6]. Because friction influ-ences water hammer in a complicated way, quantification of the phenomenon is accomplished through numerical solution of the measuration experiment in accomplicate bard theorem to accomplicate theorem and the solution of the phenomenon of the solution of the phenomenon is accomplished through numerical solution of the measuration experiment in accomplicate bard theorem to accomplicate the solution of the phenomenon of the solution of the phenomenon of the solution of the measuration of the solution of the solution of the phenomenon of the solution of the solution of the solution of the phenomenon of the solution of the solution of the solution of the phenomenon of the solution of the solution of the solution of the solution of the phenomenon of the solution of the solution of the solution of the phenomenon of the solution of the solution of the solution of the phenomenon of the solution of the solution of the solution of the phenomenon of the solution of the solution of the solution of the solution of the phenomenon of the solution of the phenomenon of the solution governing equations in academic research, and through commer-

governing equations in academic research, and through commer-cial software in practice. In the early literature on water hammer, the friction factor of the initial steady-state flow was used during transient flow. This simple approach was discussed and improved upon with unsteady friction in a large body of literature from 1968 [7] to present [8-10]. Several studies [10-13] contain comparisons between results of steady and unsteady friction models and the assessment





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Verification Reference - Watters Cover Page

MODERN ANALYSIS AND CONTROL OF UNSTEADY FLOW IN PIPELINES

Ву

GARY Z. WATTERS, PE

Professor of Civil and Environmental Engineering Utah State University Logan, Utah



Verification Reference - Wylie Cover Page

Fluid Transients in Systems

by

E. Benjamin Wylie

Professor of Civil and Environmental Engineering University of Michigan

and

Victor L. Streeter

Professor Emeritus of Hydraulics University of Michigan

with

Lisheng Suo

Associate Professor of Hydropower Engineering Hohai University; Nanjing, China



PRENTICE HALL, Englewood Cliffs, NJ 07632

Verification Methodology

The *AFT Impulse* software is a waterhammer and surge transient analysis product intended for use by trained engineers. As a technical software package, issues of quality and reliability of the technical data generated by the software are important. The following description summarizes the steps taken by Applied Flow Technology to ensure the high quality of the technical data.

1. Comparisons with open literature examples

Numerous examples of waterhammer and surge transient analysis in pipe flow systems are available in the open literature which include published results. AFT Impulse results have been compared against many open literature systems. AFT Impulse predictions compare favorably in all cases.

2. Transient solver checks for artificial transient to ensure true steady initial conditions

Before running the transient solution, AFT Impulse always runs the transient solver for a single time step with no transient boundary conditions in effect. It then compares the initial conditions to the single step calculation to see if significant differences exist. If so, a warning is generated.

3. Steady-state and transient solution at time zero are self checking

AFT Impulse has two Solvers – one for the steady-state and one for the transient. They use two entirely different solution algorithms. First the steady-state state solver is run, and then the results are used to initialize the transient solver. Before the transient solver is actually run, a sanity check is performed (as discussed in Item 2 above). If the two solvers disagree, a warning is generated. Thus is if there were fundamental calculation errors in either method then an artificial transient would be generated and the user warned. This does not ensure all transient calculations afterwards are correct, but does ensure that the fundamental transient equations are being properly represented.

Summary of Verification Models

Comparison of AFT Impulse predictions to the published calculation results is included herein for twenty-two cases from ten<u>sources</u>.

Below is a summary of the cases:

Case	Fluid	Pipes	Pumps	Reference
Case 1	Water	1	0	Wylie
Case 2	Water	2	0	Wylie
Case 3	Water	2	1	Chaudhry
Case 4	Water	1	0	Wylie
Case 5	Water	1	0	Wylie
Case 6	Water	1	0	Wylie
Case 7	Water	1	0	Wylie
Case 8	Water	1	0	Wylie
Case 9	Water	1	0	Wylie
Case 10	Water	1	0	Wylie
Case 11	Water	8	0	Karney (1992)
Case 12	Water	8	0	Karney (1992)
Case 13	Water	2	1	Watters
Case 14	Water	2	1	Wylie
Case 15	Water	5	0	Kamemura
Case 16	S.G. 1.155	1	1	Parmakian
Case 17	Water	3	1	Watters
Case 18	Water	1	0	Chaudhry
Case 19	Oil	1	0	Kaplan
Case 20	Water	2	0	Karney (1990)
Case 21	Water	7	0	Karney (1990)
Case 22	Oil	2	0	Liou

Verification Case 1

View Model Problem Statement

PRODUCT: AFT Impulse 9

TITLE:ImpVerify1.imp

REFERENCE: Fluid Transients in Systems, 1993, Prentice-Hall, E. Benjamin Wylie, Victor L. Streeter, Page 46, Example 3.1

FLUID: Water

ASSUMPTIONS: N/A

RESULTS:



DISCUSSION:

The results from AFT Impulse are compared to a simulation run by Wiley. Full details of the problem statement can be seen by clicking the link above. Close agreement can be observed in the results.

List of All Verification Models

Verification Case 1 Problem Statement

Verification Case 1

Fluid Transients in Systems, 1993, Prentice-Hall, E. Benjamin Wylie, Victor L. Streeter, Page 46, Example 3.1

Wylie's Title Page

Solution by Characteristics Method Chap. 3

3-4 Single-pipeline Applications

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The procedure to solve a transient fluid flow problem numerically involves a number of repetitious calculations. A computer program to solve a problem involving a single pipe leading from a reservoir to a valve (Fig. 3-4) has the following elements:

- 1. Read in values of data that describe the system and the character of the particular transient.
- 2. Calculate constants and initial steady-state conditions, and store initial values of Q_i and H_i for t = 0.
- 3. Print out values of Q_i and H_i at each section, plus printout time and value opening.
- 4. Increment time by $2\Delta t$, and at intermediate time Δt calculate interior points at even-numbered sections Q_2 , H_2 to Q_N , H_N .
- 5. Calculate interior points at odd-numbered sections Q_3 , H_3 to Q_{N-1} , H_{N-1} , and then calculate the boundary values Q_1 , H_1 , Q_{NS} , and H_{NS} .
- 6. Transfer back to the print statement (No. 3), or to increment time (No. 4), and check to see if T_{max} , the duration of the transient, has been exceeded. If not, continue with the calculations.



Example 3-1

The valve closure relationship for the pipeline shown in Fig. 3-4 is given by the equation

$$\tau = \tau_i - (\tau_i - \tau_f) \left(\frac{t}{t_c}\right)^{E_m}$$

in which t_c is the time of operation, τ_i the initial value of valve opening, and τ_f the final value. The steady-state open position of the valve is defined by a value of $(C_d A_G)_0$ in Eq. (3-35). The initial valve opening may be zero or any positive number, in this case $\tau_i = 1$. The input data for the problem are: L = 600 m, a = 1200 m/s, D = 0.5 m, f = 0.018, $H_R = 150$ m, $t_c = 2.1$ s, $\tau_i = 1$, $\tau_f = 0$, $T_{max} = 4.3$ s, $E_m = 0.75$, $(C_d A_G)_0 = 0.009$, g = 9.806 m/s², and N = 10.

Figure D-1 in Appendix D presents a FORTRAN listing of a program for use with MS-DOS on a PC to solve for the pressure head and flow response as a result of a specified valve motion. The input data are listed at the end of the program and are read from a separate file named SINGLE.DAT. In addition to all input data listed above, two new parameters are included. These are IPR, a control parameter that controls the number of time increments, $\Delta T = 2\Delta t$, between each printout of calculated results, and IGRAF, a section number at which pressure head data are stored for later graphing if desired.

Sec. 3-4 Single-pipeline Applications

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Steady-state discharge, Q_0 , is calculated in the program to balance the pipe friction and valve losses corresponding to $(C_d A_G)_0$ with the energy available in the reservoir. The initial flow, Q_i , for the specific problem is calculated for the given initial valve opening, τ_i .

The computer output is shown in Fig. D-1b, and a graphical display of head at the valve, discharge at the reservoir, and valve opening as a function of time are shown in Fig. 3-5.



Figure 3-5 Response in single pipeline due to valve closure.

Included in the FORTRAN program is a collection of variables to store transient information to graph if desired. These data are stored in the file attached to device 8. They include the initial pipe profile and hydraulic grade line, transient head profiles along the pipeline at each successive pair of time steps, and a time history of pressure head at section IGRAF. A separate program written in BASIC for the IBM-PC is provided in Fig. D-2, Appendix D, to read and graph these data with IBM GRAPHICS. It is a fairly primitive and simple graphics package and is provided only as a useful tool to examine transient results, not as an exposition of recommended graphic displays. The same program, called GRAF, will be available for use by other programs in this book.

Example 3-2

Consider a single horizontal pipeline as shown in Fig. 3-4 with the valve closed at the downstream end. Assume that a series of sinusoidal waves passes over the reservoir

View Verification Case 1 Model

Verification Case 1

Valve Downstream of Reservoir, Wylie, Pg 46, Example 3.1

J1		T J2
LT.	P1	
Ŧ		——M
		N N

Verification Case 2

View Model Problem Statement

PRODUCT: AFT Impulse 9

TITLE: ImpVerify2.imp

REFERENCE: Fluid Transients in Systems, 1993, Prentice-Hall, E. Benjamin Wylie, Victor L. Streeter, Page 121

FLUID: Water

ASSUMPTIONS: N/A

RESULTS:



Long Finite Pipe Termination Response



Short Pipe With Infinite Termination Response

DISCUSSION:

A long pipeline is modeled using two methods, one where the full length of the pipe is modeled, and one where two sections of the pipe are modeled with the infinite pipe method applied. It can be seen in the two graphs above that similar to Wylie, AFT Impulse gives nearly identical results for the pipe with each of the methods applied. As noted by Wylie, the infinite pipe feature can only be used up to the time when a reflection would return from the end of the pipeline.

Verification Case 2 Problem Statement

Verification Case 2

Fluid Transients in Systems, 1993, Prentice-Hall, E. Benjamin Wylie, Victor L. Streeter, Page 121

Wylie Title Page

Sec. 6-2 Infinite Pipeline

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6-2 Infinite Pipeline

In a long pipeline system the analyst may be interested in the transient details locally and not in the long-term behavior of the extended system. Under these conditions it is helpful to use an alternative model,¹⁶ but one that will respond similarly to the long pipe. This substitute element, which is to respond like the long pipe, is useful only up until a reflection would return from the other extremity of the long pipe (i.e., until 2L/aseconds), where L and a refer to the actual long line.

Conceptually, the characteristic impedance of the pipeline should provide the desired termination. However, the impedance B in the relationship $\Delta H = \pm B \Delta Q$ is valid only for frictionless systems. Figure 6-8 provides a sketch in which the desired termination would be located at point U, two distance intervals upstream from the exciter in the system. For illustration purposes a valve has been used for the exciter in this high-friction system, although it could be a pump or any other dynamic element.

Inasmuch as the only reflections in the system are from the friction gradient, any disturbances created at the exciter, point D, pass upstream only. Therefore, values of the variables at point I (Fig. 6-8), are extrapolated along a characteristic line beyond the modeled pipe termination one Δx . Although a linear extrapolation produces reasonable results, second order is better and is recommended:

$$H_1 = 3H_1 - 3H_2 + H_3$$
 $Q_1 = 3Q_1 - 3Q_2 + Q_3$ (6-11)





Complex Systems with Multipipe and Nonpipe Elements Chap. 6

With values of the variables at point I available, a standard C^+ compatibility equation can be used, and a typical interior point calculation can be performed at section *i*.

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Figure 6-9 shows results from an example with a rapid valve closure at t = 0.2 s and rapid opening to $\tau = 0.5$ at t = 4.2 s in the pipe in Fig. 6-8. The data are L = 4800 m, D = 0.2 m, f = 0.018, a = 1200 m/s, $Q_0 = 0.210$ m³/s, $H_0 = 27.88$ m, N = 40. Three different results at the valve are shown in Fig. 6-9: the actual values from the long pipe simulation, the values with the infinite pipe model as described above, and the values from use of the characteristic impedance termination. The latter two terminations were located at point U, 240 m upstream from the valve.

This represents a high-friction system, $f \Delta x Q_0/2DAa = 0.03$, and it is seen that the results from the infinite pipe termination are indistinguishable in the sketch. The largest discrepancy, of approximately 2.9 m, occurred at the end of the simulation. For slower transients or lower-friction cases the results would be considerably better. Use of the pipeline impedance, although perfect in the frictionless case, is seen to be unacceptable in this high-friction rapid transient.

View Verification Case 2 Model

Verification Case 2



Verification Case 3

View Model Problem Statement

PRODUCT: AFT Impulse 9

TITLE:ImpVerify3.imp

REFERENCE: M. H. Chaudhry, Applied Hydraulic Transients, 3rd ed. Springer, pp. 131, 535-543.

FLUID: Water

ASSUMPTIONS: N/A

RESULTS:



Verification Case 3



DISCUSSION:

The results from AFT Impulse are compared to a simulation run by Chaudhry. Full details of the problem statement can be seen by clicking the link above. Close agreement can be observed in the results.

Verification Case 3 Problem Statement

Verification Case 3

M. H. Chaudhry, Applied Hydraulic Transients, 3rd ed. Springer, pp. 131, 535-543.

Chaudhry Title Page

540	C TRANSIENTS CAUSED BY POWER FAILURE TO PUMPS	C-3 Progra
	VE=VE+DV	1.269,1.240,1.201,1.162,1.115,1.069,1.025,0.992,0.945,0.908,0.875,
	IF (ABS(DV).LE.0.001.AND.ABS(DALPHA).LE.0.001) GO TO 50 IF (JJ.GT.30) GO TO 70	0.848,0.819,0.788,0.755,0.723,0.690,0.656,0.619,0.583,0.555,0.531,
50	GO TO 8 TH=ATAN2 (ALPHAE, VE)	0.510,0.502,0.500,0.505,0.520,0.539,0.565,0.593,0.615,0.634,0.640,
	IF (TH.LT.O.0) TH=TH+360. CALL PARAB (TH.2. BETA)	0.638,0.630
	MB=TH/DTH+1 BETA= BETA * (ALPHA+ALPHA+V*V)	-0.350, -0.474, -0.180, -0.062, 0.037, 0.135, 0.228, 0.320, 0.425, 0.500, 0.548, 0.000, 0.0
	IF (MB.EQ.M) GO TO 60 GO TO 8	0.588,0.612,0.615,0.600,0.569,0.530,0.479,0.440,0.402,0.373,0.350,0.34,
60	DALPHA=ALPHAE-ALPHA DV=VE-V	0.34,0.35,0.38,0.437,0.52,0.605,0.683,0.75,0.802,0.845,0.872,0.883,0.878,
	ALPHA=ALPHAE V=VE	0.86,0.823,0.78,0.725,0.66,0.58,0.49,0.397,0.31,0.23,0.155,0.085,0.018,
70	RETURN	-0.052,-0.123,-0.22,-0.348,-0.49,-0.68
80	FORMAT(8X,'**'ITERATIONS IN PUMP SUBROUTINE FAILED'/8X,'T=',F8.2 2/8X,'ALPHAE =',F6.3/8X,'VP =',F6.3)	450.0,0.75,900.0,0.01
	STOP END SUBROUTINE PARAB(X, J, Z) COMMON /PAR/FH, FB, DX DIMENSION FH(60), FB(60) $I \approx X/DX$ $R = (X - I^+ DX) / DX$	550.0,0.75,1100.0,0.012
	IF(I.EQ.0) R=R-1. I=I+1 IF(I.LT.2) I=2	C-3 Program Output
10	GO TO (10,20), J Z=FH(I)+0.5*R*(FH(I+1)-FH(I-1)+R*(FH(I+1)+FH(I-1)-2.*FH(I)))	
20	Z=FB(I)+0.5*R*(FB(I+1)-FB(I-1)+R*(FB(I+1)+FB(I-1)-2.*FB(I))) RETURN END	NUMBER OF PIPES = 2 NUMBER OF REACHES ON LAST PIPE = 2 STEADY STATE DISCH. = .500 M3/S STEADY STATE FUMP SPEED =1100.0 RPM TIME FOR WHICH TRANS. STATE COND. ARE TO BE COM NUMBER OF PARALLEL PUMPS = 2
		NUMBER OF POINTS ON CHARACTERISTIC CURVE = 55 THETA INTERVAL FOR STORING CHARACTERISTIC CURVE RATED DISCH. = .25 M3/2 RATED HEAD = 60.0 M BATED FIND SEPED =1100 0 BEM
C-2	Input Data	PUMP EVER SPEED #1100.0 RPM PUMP EFFCIENCY = .840 WE2= 16.85 KG-M2

2,2,2,2,9.81,0.5,1100.0,15.0 55,5.0,0.250,60.0,1100.0,0.84,16.85 -0.53,-0.476,-0.392,-0.291,-0.150,-0.037,0.075,0.200,0.345, 0.500,0.655,0.777,0.9,1.007,1.115,1.188,1.245,1.278,1.290,1.287,

ıt ES = 2 CHES ON LAST PIPE = 2 DISCH. = .500 M3/S PUMP SPEED =1100.0 RPM H TRANS. STATE COND. ARE TO BE COMPUTED = 15.0 S ALLEL PUMPS = 2 NTS ON CHARACTERISTIC CURVE = 55 L FOR STORING CHARACTERISTIC CURVE = 5. = .25 M3/S 60.0 M

C-3 Program Output

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RATED PU PUMP EFF WR2= 16	MP SPEE TCIENCY 5.85 KG-	D =1100 = .84 -M2	0 RPM					
POINTS C	N HEAD	CHARACT	. CURVE					
530	476	392	291	150	037	.075	.200	.345
.655	.777	.900	1.007	1.115	1.188	1.245	1.278	1.290
1000			11007		11100	21230	1.12.70	11250
1.269	1.240	1.201	1.162	1.115	1.069	1.025	.992	.945
975	849	919	799	755	723	690	65.6	610
.015	.040	.019	. /00	. 155	.725	.030	.050	.019
.555	.531	.510	.502	.500	.505	.520	.539	.565
615	634	640	638	630				
	RATED PU PUMP EFF WR2= 16 POINTS C 530 .655 1.269 .875 .555 .615	RATED PUMP SPEE PUMP EFFICIENCY WR2= 16.85 KG POINTS ON HEAD 530476 .655 .777 1.269 1.240 .875 .848 .555 .531 .615 .634	EATED FUNK SPEED -1100 FUNK EFFICIENCY = .84 WR2= 16.85 KG-M2 POINTS ON HEAD CHARACT 530476392 .655 .777 .900 1.269 1.240 1.201 .875 .848 .819 .555 .531 .510 .615 .634 .640	PATED PONG SPEED -110.0 RPM PUMP EFFICIENCY840 WR2- 16.85 KG-M2 POINTS ON HEAD CHARACT. CURVE 530476392291 .655 .777 .900 1.007 1.269 1.240 1.201 1.162 .875 .848 .819 .786 .555 .531 .510 .502 .615 .634 .640 .638	PATED PUNP SPEED -110.0 RPM PUMP EFFICIENCY840 POINTS ON HEAD CHARACT. CURVE 530476392291150 .655 .777 .900 1.007 1.115 1.269 1.240 1.201 1.162 1.115 .875 .848 .819 .788 .755 .555 .531 .510 .502 .500 .615 .634 .640 .638 .630	RATED FUND SPEED -1100.0 RPM FUND EFFICIENCY840 WM2- 16.85 KG-M2 POINTS ON HEAD CHARACT. CURVE 530476392291150037 .655 .777 .900 1.007 1.115 1.188 1.269 1.240 1.201 1.162 1.115 1.069 .875 .848 .819 .788 .755 .723 .555 .531 .510 .502 .500 .505 .615 .644 .640 .638 .630	RATED FUND SPEED =1100.0 RFM FUND EFFICIENCY = .840 WR2= 16.85 KG-M2 POINTS ON LEAD CHARACT. CURVE 530476392291150037 .075 .655 .777 .900 1.007 1.115 1.188 1.245 1.269 1.240 1.201 1.162 1.115 1.069 1.025 .875 .848 .819 .788 .755 .723 .690 .555 .531 .510 .502 .500 .505 .520 .615 .634 .640 .638 .630	RATED FUNC SPEED -1100.0 RPM PUPP EFFICIENCY = .840 POINTS ON HEAD CHARACT. CURVE 530476392291150037 .075 .200 .655 .777 .900 1.007 1.115 1.188 1.245 1.278 1.269 1.240 1.201 1.162 1.115 1.069 1.025 .992 .875 .848 .819 .788 .755 .723 .690 .656 .555 .531 .510 .502 .500 .505 .520 .539 .615 .634 .640 .638 .630

	POINTS	ON TOR	QUE CHAN	RACT. CU. 0062	RVE .037	.135	.228	.320	.425	
500	54	8 58	8 .61	2 .615	.600	.569	.530	.479	.440	
402		2 25	0 24	0 340	350	380	.437	.520	.605	
683	. 37			e .540	003	979	860	823	.780	
725	.75	0.80	2 .84	5 .072	.003	.070	165	0.95	018	
.052	.66	.58	0.49	0.397	.310	.230	.155	.005	.010	
	12	322	034	8490	680					
	PIPE N	10 I	ENGTH (M)	DIA (M)	WAVE (M)	VEL. (S)	FRI C	FACTO	R	
	1		450.0	.75	900	0.0		010		
	2		550.0	. /5	1100					
	PIPE N	10 7	ADJUSTED (M	WAVE VE 1/S)	L.					
	1 2		9	00.0 00.0						
	TIME	ALPHA	v	PIPE	HEAD	(M)	DISCH	. (M3/	/S)	
				NO.	(1)	(N+1)	(1)	(1)	N+1)	
	.0	1.00	1.00	1	60.0	59.6	.500		.500	
	.5	.69	.69	1	28.3	59.6	.347		.500	
	1.0	.52	.57	2	14.8	24.9	.283		.363	
	1.5	.42	.56	2	24.9	59.0	.363		.305	
	2.0	.36	. 55	2	10.0	59.0 36.6	.305		.227	
	2.0			2	36.6	59.0	.139		.111	
	2.5	.31	.00	2	47.5	59.0	.066		.050	
	3.0	.29	24	2	24.7	59.0	085		.020	
	3.5	.26	32	1 2	9.4	15.2 59.0	159	-	.152	
	4.0	.21	36	1 2	9.2	38.8 59.0	181	-	.300	
	4.5	.11	73	1	24.6	48.0	367	-	.367	
	5.0	09	89	1	31.3	41.4	446	-	.447	
	5.5	34	96	1	34.5	39.6	479	-	.484	
	6.0	58	97	2 1	39.6 39.0	59.0 49.6	484	-	.549	
	6.5	81	-1.06	2	49.6	59.0 56.3	549	-	.558	
		-1.02	-1.05	2	56.3	59.0	566		.584	
	7.0	-1.02	-1.05	2	62.0	59.0	569	-	.574	
	7.5	-1.19	-1.00	1 2	67.8	59.0	502	-	.554	
	8.0	-1.31	93	1 2	82.7	74.0	463		.492	
	0.5		0.0		07.5	70 1	- 420		- 430	

					C-3	Program C	output	5
			2	76.1	50.0	120	121	
9.0	-1.39	- 76	1	86.5	74 9	- 379	- 367	
			2	74.9	59.0	- 367	- 361	
9.5	-1.37	66	1	82.1	72.1	= 332	- 309	
		100	2	72 1	59.0	- 308	- 304	
10.0	-1.32	- 59	1	75 2	69 5	- 293	- 266	
1010	2102		2	68.5	59.0	- 266	- 256	
10.5	-1.26	- 53	1	68 1	63 7	- 267	- 237	
		100	2	63.7	59.0	237	- 228	
11.0	-1.20	50	1	61.4	59 5	- 248	- 226	
			2	59.5	59.0	- 226	- 218	
11.5	-1.15	- 48	1	56.0	56 9	- 242	- 226	
		.40	2	56.9	59.0	- 226	- 223	
12.0	-1.10	50	1	52.3	55.2	- 248	- 238	
			2	55 2	59.0	- 238	- 234	
12.5	-1.07	52	ĩ	50.3	53.7	- 261	= 254	
			2	53.7	59.0	- 254	- 253	
13.0	-1.06	55	1	49.4	53.2	- 275	- 275	
			2	53.2	59.0	275	- 275	
13.5	-1.05	58	1	49.7	53.7	- 291	- 295	
			2	53.7	59.0	295	297	
14.0	-1.06	62	1	50.9	54.5	308	314	
			2	54.5	59.0	314	315	
14.5	-1.08	64	1	52.8	55.4	322	328	
			2	55.4	59.0	328	331	
15.0	-1.10	66	1	54.9	56.6	-,330	339	
			2	56.6	59.0	339	342	
PIP	E NO.	MAX.	PRESS.	MII	N. PRESS			
			M)		(M)			
	1	87.	4		1.0			
	2	76.	1	10	0.0			

View Verification Case 3 Model

Verification Case 3

M. H. Chaudhry, Applied Hydraulic Transients, 3rd ed. Springer, pp. 131, 535-543. Transients Caused by Power Failiure to Pumps.



Verification Case 4

View Model Problem Statement

PRODUCT: AFT Impulse 9

TITLE: ImpVerify4.imp

REFERENCE: Fluid Transients in Systems, 1993, Prentice-Hall, E. Benjamin Wylie, Victor L. Streeter, Page 195, Example 8-5

FLUID: Water

ASSUMPTIONS: Valve is described as "fast closing". Closing profile is not specified. Impulse model assumes instantaneous closure.

RESULTS:



HGL at x=L (at Valve)

Verification Case 4



DISCUSSION:

This experiment was designed to cause transient cavitation, and the flow does cavitate. As is common with cavitation modeling the timing of pressure spikes is marginal, but the major features and magnitude of prominent spikes is represented.
Verification Case 4 Problem Statement

Verification Case 4

Fluid Transients in Systems, 1993, Prentice-Hall, E. Benjamin Wylie, Victor L. Streeter, Page 195

Wylie Title Page

Sec. 8-4 Column Separation in Liquids with No Free Gas; Isolated Cavities 195

cavities at fixed locations, although there may be minor variations in computing results, depending on the number of reaches, upon the manner in which the void space volume is calculated, and so on.²⁰

Although the early time transient in this example shows a void space only at the endpoint, it is possible to produce vapor at other positions in the system as a result of intersecting low-pressure waves. This may be illustrated by following case (b) for a few more wave reflections after the first pressure rise. The literature^{3,12,13,18,21,22} contains evidence of the physical existence of such intermediate cavities as well as distributed vaporous zones as discussed in the next section.

The main strength of the discrete vapor cavity model in Sec. 3-8 lies in its simplicity. The discrete gas cavity model presented in Sec. 8-2 has also been utilized with some degree of success in analyzing vaporous cavitation problems of this nature, as well as with distributed vaporization, as discussed in the next section.^{16,31} By reducing the free-gas content in the discrete gas cavity model, the presence of the free gas is inconsequential until the local pressure drops to a level near vapor pressure. Typically, a void fraction of 10⁻⁷ at standard atmospheric conditions is used. At this level the wavespeed remains at 99, 96, and 88 percent of the pure liquid wave speed until the pressure drops below 0.2, 0.1, and 0.05 of atmospheric pressure, respectively. In inertially dominated transient events, with forces that would yield large negative pressures if physically permitted, the discrete gas cavity model yields a pressure that converges asymptotically to the actual liquid vapor pressure as the discrete volumes expand. This is in keeping with true physical behavior, where the discrete volumes would be occupied by air and vapor. The next example illustrates the dynamics of an isolated vapor cavity in a single line, by examining results from a physical experiment¹⁹ and by providing a comparison to numerical results from the discrete gas cavity model.

Example 8-5

These data are obtained from an experiment¹⁹ on a 36-m-long 19.05-mm-ID copper tubing. The pipeline had an upward slope of 1 m, with a fast-closing, $\frac{1}{2}$ -in. one-quarter-turn ball valve at the downstream end and a constant-pressure tank at the upstream end. Steady-state friction-drop experiments were taken, and for this initial velocity of 0.332 m/s the friction factor was 0.0315. The upstream ends wave head was 23.41 m and the vapor pressure is -9.82 m. The measured wavespeed in the liquid-filled pipeline was 1280 m/s.

With the active valve at the downstream end, vaporization occurs at the valve upon return of the rarefaction wave from the reservoir. In this low-velocity (low-friction) case the wave propagates to a higher-pressure region, so vaporization is limited to the valve location, at least until collapse of the first vapor cavity. Figure 8-10 shows experimental results at the valve and at 9 m from the upstream end, and numerical results utilizing the discrete gas cavity model with $\alpha = 10^{-7}$ at standard conditions, N = 16, as described in Sec. 8-2.

The experimental results show the peak pressure change following collapse of the vapor eavity to be clearly in excess of aV_0/g . Also, numerical results compare favorably with experimental data.



Figure 8-10 Comparison of experimental results (solid line), Simpson,¹⁹ with discrete gas cavity model.

8-5 Mechanics of Distributed Vaporization

A distributed vaporous cavitation region in a liquid-filled pipeline occurs when a rarefaction wave drops the pressure in an extended region of the pipeline to vapor pressure. Inasmuch as the void fraction, α , remains near zero, this regime is distinctly different from isolated column separation, which normally occurs at well-defined sections in a system such as high points, at valves or dead ends, and may also occur at locations in the pipeline where two low-pressure waves traveling in opposite directions intersect. Distributed vaporization is best visualized by examining a numerical example.

Figure 8-11 illustrates a physical system in which the pipeline is sloping upward, 4 m, in the direction of flow. When the initial inflow of 0.4 m/s is stopped at the upstream end, the pressure drops to vapor pressure, but with the upward-sloping pipe, the full-magnitude 25-m wave cannot propagate into the pipeline since the lower limit

View Verification Case 4 Model

Verification Case 4

Valve Closu	ure w/ Vapor Ca	vity Formation, Wyli	e Pg. 195
J1		T J2	
Ť	P1	⊳	

View Model Problem Statement

PRODUCT: AFT Impulse 9

TITLE: ImpVerify5.imp

REFERENCE: Fluid Transients in Systems, 1993, Prentice-Hall, E. Benjamin Wylie, Victor L. Streeter, Page 202, Example 8-6

FLUID: Water

ASSUMPTIONS: N/A

RESULTS:



DISCUSSION:

This example was designed to cause transient cavitation, and the flow does cavitate. As is common with cavitation modeling the timing of pressure spikes is marginal, but the major features and magnitude of prominent spikes is represented.

Verification Case 5 Problem Statement

Verification Case 5

Fluid Transients in Systems, 1993, Prentice-Hall, E. Benjamin Wylie, Victor L. Streeter, Page 202, Example 8-6

Wylie Title Page

202 Two-Component and Single-Component Two-Phase Transient Flows Chap. 8

at 15.0 m, the upstream pipe elevation at zero, and L = 980 m, a = 980 m/s, D = 1.1284 m, f = 0.03, and $H_v = -10.0$ m. In the discrete gas cavity model $\psi = 1$ and $\alpha = 10^{-7}$ at atmospheric pressure.

Example 8-6

In this case the change in elevation $\Delta z = 4.0$ m, and $V_0 = 0.4$ m/s. Figure 8-14 provides a comparison of the two computational procedures with N = 20. Reasonable agreement exists between the two methods. The vaporous zone is sustained only slightly longer than 2L/a seconds (to 2.22 s) in the upstream region of the pipe and the void fraction grows to only about 0.0002 before collapsing. The isolated cavity exists for approximately 2.9 s. It may be noted that the pressure exceeds a maximum of 55 m ($aV_0/g + H_0$).



Figure 8-14 Example 8-6, distributed vaporization, $V_0 = 0.4$ m/s, $\Delta Z = 4.0$ m.

Example 8-7

In this case $\Delta z = 4.0$ m and $V_0 = 1.56$ m/s. Figure 8-15 shows general agreement in results. The vaporous zone is sustained for 2.33 s and the isolated cavity exists until 12.2 s. The pressure rise is approximately what might be expected from stopping the original flow abruptly.

Example 8-8

The rising slope is increased to $\Delta z = 12.0$ m, and $V_0 = 1.48$ m/s. The void fraction reaches 0.001 in the distributed vaporization zone, which lasts until approximately 3.71 s. The isolated cavity lasts until approximately 11.8 s. The pressure trace at the upstream end is shown in Fig. 8-16 for both analyses. Again the agreement in timing is reasonable and the pressure magnitudes are similar.

The detailed modeling, provided in the distributed vapor model, is superior in these examples since it provides a reasonable description of the physical behavior.

View Verification Case 5 Model

Verification Case 5

Cavitation in	Elevated Pipes, Wylie Po	g. 202, Example 8-6
TJ1		J2
0	P1	

View Model Problem Statement

PRODUCT: AFT Impulse 9

TITLE: ImpVerify6.imp

REFERENCE: Fluid Transients in Systems, 1993, Prentice-Hall, E. Benjamin Wylie, Victor L. Streeter, Page 202, Example 8-7

FLUID: Water

ASSUMPTIONS: N/A

RESULTS:



DISCUSSION:

This example was designed to cause transient cavitation, and the flow does cavitate. As is common with cavitation modeling the timing of pressure spikes is marginal, but the major features and magnitude of prominent spikes is represented.

Verification Case 6 Problem Statement

Verification Case 6

Fluid Transients in Systems, 1993, Prentice-Hall, E. Benjamin Wylie, Victor L. Streeter, Page 202, Example 8-7

Wylie Title Page

202 Two-Component and Single-Component Two-Phase Transient Flows Chap. 8 at 15.0 m, the upstream pipe elevation at zero, and L = 980 m, a = 980 m/s, D = 1.1284 m, f = 0.03, and $H_{\nu} = -10.0$ m. In the discrete gas cavity model $\psi = 1$ and $\alpha = 10^{-7}$ at atmospheric pressure. Example 8-6 In this case the change in elevation $\Delta z = 4.0$ m, and $V_0 = 0.4$ m/s. Figure 8-14 provides

In this case the change in elevation $\Delta z = 4.0$ m, and $V_0 = 0.4$ m/s. Figure 8-14 provides a comparison of the two computational procedures with N = 20. Reasonable agreement exists between the two methods. The vaporous zone is sustained only slightly longer than 2L/a seconds (to 2.22 s) in the upstream region of the pipe and the void fraction grows to only about 0.0002 before collapsing. The isolated cavity exists for approximately 2.9 s. It may be noted that the pressure exceeds a maximum of 55 m ($aV_0/g + H_0$).





Example 8-7

In this case $\Delta z = 4.0$ m and $V_0 = 1.56$ m/s. Figure 8-15 shows general agreement in results. The vaporous zone is sustained for 2.33 s and the isolated cavity exists until 12.2 s. The pressure rise is approximately what might be expected from stopping the original flow abruptly.

Example 8-8

The rising slope is increased to $\Delta z = 12.0$ m, and $V_0 = 1.48$ m/s. The void fraction reaches 0.001 in the distributed vaporization zone, which lasts until approximately 3.71 s. The isolated cavity lasts until approximately 11.8 s. The pressure trace at the upstream end is shown in Fig. 8-16 for both analyses. Again the agreement in timing is reasonable and the pressure magnitudes are similar.

The detailed modeling, provided in the distributed vapor model, is superior in these examples since it provides a reasonable description of the physical behavior.



However, it is fraught with numerical coding difficulties when modeling more general cases. Thus the discrete gas cavity model, with a low mass of free gas, offers a convenient alternative, and it is simple to implement. It is seen that it simulates these cases reasonably well, and the model is fairly robust. It should be used with caution and with understanding, as it, too, may yield excessive numerical oscillations in cases with distributed vaporization at large void fractions.

View Verification Case 6 Model

Verification Case 6

Cavitation in Elevated Pipes, Wylie Pg. 202, Example 8-7

View Model Problem Statement

PRODUCT: AFT Impulse 9

TITLE: ImpVerify7.imp

REFERENCE: Fluid Transients in Systems, 1993, Prentice-Hall, E. Benjamin Wylie, Victor L. Streeter, Page 202, Example 8-8

FLUID: Water

ASSUMPTIONS: N/A

RESULTS:



DISCUSSION:

This example was designed to cause transient cavitation, and the flow does cavitate. As is common with cavitation modeling the timing of pressure spikes is marginal, but the major features and magnitude of prominent spikes is represented.

Verification Case 7 Problem Statement

Verification Case 7

Fluid Transients in Systems, 1993, Prentice-Hall, E. Benjamin Wylie, Victor L. Streeter, Page 202, Example 8-8

Wylie Title Page





Example 8-7

In this case $\Delta z = 4.0$ m and $V_0 = 1.56$ m/s. Figure 8-15 shows general agreement in results. The vaporous zone is sustained for 2.33 s and the isolated cavity exists until 12.2 s. The pressure rise is approximately what might be expected from stopping the original flow abruptly.

Example 8-8

The rising slope is increased to $\Delta z = 12.0$ m, and $V_0 = 1.48$ m/s. The void fraction reaches 0.001 in the distributed vaporization zone, which lasts until approximately 3.71 s. The isolated cavity lasts until approximately 11.8 s. The pressure trace at the upstream end is shown in Fig. 8-16 for both analyses. Again the agreement in timing is reasonable and the pressure magnitudes are similar.

The detailed modeling, provided in the distributed vapor model, is superior in these examples since it provides a reasonable description of the physical behavior.



However, it is fraught with numerical coding difficulties when modeling more general cases. Thus the discrete gas cavity model, with a low mass of free gas, offers a convenient alternative, and it is simple to implement. It is seen that it simulates these cases reasonably well, and the model is fairly robust. It should be used with caution and with understanding, as it, too, may yield excessive numerical oscillations in cases with distributed vaporization at large void fractions.

View Verification Case 7 Model

Verification Case 7

Cavitation in Elevated Pipes, Wylie Pg. 202, Example 8-8

TJ1 J2 ₽1 ▼

View Model Problem Statement

PRODUCT: AFT Impulse 9

TITLE: ImpVerify8.imp

REFERENCE: Fluid Transients in Systems, 1993, Prentice-Hall, E. Benjamin Wylie, Victor L. Streeter, Page 204

FLUID: Water

ASSUMPTIONS: The problem statement from Wylie does not specify the valve closing transient. It says merely that "most" of the flow reduction occurs in the first 16 ms, and that the valve fully closes after 39 ms. It was therefore estimated that "most" means that the valve closes linearly to 3% open over 16 ms, and then linearly to fully closed at 39 ms.

RESULTS:





DISCUSSION:

This experiment was designed to cause transient cavitation, and the flow does cavitate. As is common with cavitation modeling the timing of pressure spikes is marginal, but the major features and magnitude of prominent spikes is represented.

Verification Case 8 Problem Statement

Verification Case 8

Fluid Transients in Systems, 1993, Prentice-Hall, E. Benjamin Wylie, Victor L. Streeter, Page 204

Wylie Title Page

204 Two-Component and Single-Component Two-Phase Transient Flows Chap. 8

8-6 Additional Vaporization Examples

Experimental results are presented for two cases, with comparisons to the discrete free-gas cavity model. Simpson¹⁹ provided several examples of experimental results using the apparatus described in Example 8-5, with initial velocities larger than in that case. With sufficiently high velocities the pressure gradient in this particular system at the time of vaporization, 2L/a seconds, is such that the hydraulic gradient and the pipeline converge in the direction of vaporization, the upstream direction. A combination of a distributed vaporization zone and a discrete downstream cavity develop and subsequently collapse. Simpson's original material¹⁹ may be referred to for additional comparisons with experimental results in this apparatus. The second example involves an experiment in the Delft Hydraulics Laboratory, simulating pump failure and restarting of a pump at the upstream end of a horizontal test pipeline. In this case the upstream pressure reduction pulse, which simulates the pump failure, rides down the steady pressure gradient. An interior distributed vaporous zone develops when the low-pressure wave reaches vapor pressure. An isolated cavity does not develop.

Example 8-9

For this case, in the test apparatus as described in Example 8-5, $V_0 = 1.125$ m/s, f = 0.023, upstream pressure head 21.74 m, and vapor pressure -9.83 m. Velocity variation at the valve during valve closure was determined numerically by Simpson¹⁹ with the downstream measured pressure head specified. In this case, flow is reduced to zero in about 39 ms, with most of flow reduction occurring in about 16 ms. The wave reflection time is approximately 56 ms in the system.

Figure 8-17 shows the experimental results at the valve and at 9 m from the upstream end, and numerical results utilizing the discrete gas cavity model with N = 16 and $\alpha = 10^{-7}$ at standard conditions. Although the agreement is reasonable, the timing is slightly off for each of the pressure peaks following cavity collapse, and the numerical results produce a short-duration pressure peak at the valve at about 0.35 s that does not appear in the experimental record.

In the pressure history at the valve during the first high-pressure pulse following valve closure it is noted that there is a divergence between the experimental and calculated results. In fact, the pressure reduction displayed in the experimental trace is unrealistic for a nondeforming pipeline system during the first 2L/a seconds. To be more confident that the discrete gas cavity model was simulating the same problem as the physical experiment, it was decided to calculate the velocity variation at the valve necessary to produce the measured pressure history until the instant of return of the first major rarefaction wave. This resulted in a positive flow at the valve even after the valve was closed. A volume of approximately 0.5 cc of liquid was removed from the system, which corresponds to an elongation of the pipeline during this period. Since this volume represented an additional temporary storage capacity at the valve end, it had to be returned to the system during the low-pressure part of the cycle, when the short-term longitudinal strain is relaxed. Since a vapor space exists at the valve during this time the manner in which the volume is reintroduced is arbitrary. This velocity pattern was used at the valve for the simulation shown in Fig. 8-18; that is, the flow was stopped in 39 ms, then the additional volume of 0.5 cc was removed over the next 46 ms in a manner that provided agreement between the two pressure traces. From that point on, the valve was considered a dead end. Clearly,



Figure 8-17 Example 8-9, comparison of experimental results (solid line), Simpson,¹⁹ with discrete gas cavity model, $V_0 = 1.125$ m/s.

there must be similar deformation at the valve during each of the high-pressure pulses, but short of a complete fluid-structure interaction calculation, there is no reliable way to calculate the actual velocity history during these deformations. This second simulation (Fig. 8-18) provides closer pressure magnitude agreement with the measured experimental values, but the timing is advanced.

These comparisons demonstrate once again that there are many features present in experimental results that represent the combined response of the system. It is asking too much of a vaporization model, even if 100 percent accurate, to reproduce, religiously, experimental results that include the combined influences of other important phenomena.

Example 8-10

From the literature^{9,15} experimental results are available in a horizontal test pipe in the Delft Hydraulics Laboratory for a simulated pump failure and pump restart. At the upstream end a pressure-time pattern was specified to simulate the pump behavior. A

View Verification Case 8 Model

Verification Case 8

Valve Closure w/ Va	apor Cavity	Formation, Wylie Pg. 204
J1	P1	T J2
· · · · · · · · · · · · · · · · · · ·		₩

View Model Problem Statement

PRODUCT: AFT Impulse 9

TITLE: ImpVerify9.imp

REFERENCE: Fluid Transients in Systems, 1993, Prentice-Hall, E. Benjamin Wylie, Victor L. Streeter, Page 205, Example 8-10

FLUID: Water

ASSUMPTIONS: Downstream pressure constant at 64 kPa. Problem statement is merely that the downstream pressure is fixed, but the actual value is not given. To achieve the given flowrate of 0.0158 m3/sec, a pressure of 64 kPa is required. Unfortunately, the initial HGL at the specified locations of 30 and 10 meters was not able to be matched. Thus the Impulse results shown below are likely off in the vertical direction to some degree. Nevertheless, Impulse predictions follow the major trends quite well.

RESULTS:



Cavitation Due to Pump Transients Upstream, x=0.4L



Cavitation in Pipe due to Pump Transient Upstream, x=.8L

DISCUSSION:

This experiment was designed to cause transient cavitation, and the flow does cavitate. As is common with cavitation modeling the timing of pressure spikes is marginal, but the major features and magnitude of prominent spikes is represented.

Verification Case 9 Problem Statement

Verification Case 9

Fluid Transients in Systems, 1993, Prentice-Hall, E. Benjamin Wylie, Victor L. Streeter, Page 205, Example 8-10

Wylie Title Page



Figure 8-17 Example 8-9, comparison of experimental results (solid line), Simpson,¹⁹ with discrete gas cavity model, $V_0 = 1.125$ m/s.

there must be similar deformation at the valve during each of the high-pressure pulses, but short of a complete fluid-structure interaction calculation, there is no reliable way to calculate the actual velocity history during these deformations. This second simulation (Fig. 8-18) provides closer pressure magnitude agreement with the measured experimental values, but the timing is advanced.

These comparisons demonstrate once again that there are many features present in experimental results that represent the combined response of the system. It is asking too much of a vaporization model, even if 100 percent accurate, to reproduce, religiously, experimental results that include the combined influences of other important phenomena.

Example 8-10

From the literature^{9,15} experimental results are available in a horizontal test pipe in the Delft Hydraulics Laboratory for a simulated pump failure and pump restart. At the upstream end a pressure-time pattern was specified to simulate the pump behavior. A



Figure 8-18 Example 8-9, comparison of experimental results (solid line), Simpson,¹⁹ with discrete gas cavity model, $V_0 = 1.125$ m/s. Flow specified for approximately 0.1 s.

large pressure tank provided constant downstream pressure. The system data include D = 0.10 m, L = 1450 m, f = 0.018, $Q_0 = 0.0158 \text{ m}^3/\text{s}$, a = 1290 m/s, $\rho = 1000 \text{ kg/m}^3$, $H_R^* = 60.2 \text{ m}$, z = 0.0 m, $H_v = -10.10 \text{ m}$, $\alpha_0 = 10^{-7}$ at standard conditions, and N = 20. Figure 8-19 shows the experimental record at x = 0.4L and at x = 0.8L, as well as the upstream controlled pressure. In addition, the numerical results from the discrete gas cavity model are presented with $\psi = 1.0.^{31}$ Agreement is observed to be quite acceptable. The same experimental results have been compared with numerical results from a vapor

Experimental data on column separation are presented by many others for both pure liquid transients and for cases with free and evolving gases. Some of the physical measurements indicate considerably more dissipation than in analytical studies. The example by Li^{10} presented in Fig. 3-24 lacks agreement after the first cavity collapse.

column separation model (no free gas other than vapor).32



Figure 8-19 Example 8-10, distributed vaporization in a horizontal pipeline.

Baltzer² and Weyler²⁷ provide similar results. Swaffield²⁵ and Driels⁵ have reported experimental comparisons with kerosene as the liquid. Kranenburg⁹ indicates the need for gas release to bring about better correlation between theory and experiment, as do Wiggert and Sundquist.²⁸ A note of caution may be in order when attempting to match numerical results with experimental records. The collapse of vapor pockets in pipelines represent one of the few examples of truly instantaneous transients. With such a rapid transient event several dissipative mechanisms, normally unimportant, may be significant. Some of these include frequency-dependent viscous losses, frequency-dependent elastic wall properties, viscoelastic wall properties, and fluid–structure interaction, among others.

The situation shown in Fig. 8-20 may arise with rapid valve closure at the upstream end of a short pipe. Most of the liquid escapes, but a portion is trapped in the



Figure 8-20 Trapped column of liquid in short line.

View Verification Case 9 Model

Verification Case 9



View Model Problem Statement

PRODUCT: AFT Impulse 9

TITLE: ImpVerify10.imp

REFERENCE: Fluid Transients in Systems, 1993, Prentice-Hall, E. Benjamin Wylie, Victor L. Streeter, Page 69, DVC Model Case

FLUID: Water

ASSUMPTIONS: N/A

RESULTS:



DISCUSSION:

This experiment was designed to cause transient cavitation, and the flow does cavitate. As is common with cavitation modeling the timing of pressure spikes is marginal, but the major features and magnitude of prominent spikes is represented.

Verification Case 10 Problem Statement

Verification Case 10

Fluid Transients in Systems, 1993, Prentice-Hall, E. Benjamin Wylie, Victor L. Streeter, Page 69, DVC Model Case

Wylie Title Page

Sec. 3-9 Algebraic Method

69

lists the FORTRAN code for an internal section calculation. End conditions are handled similarly.

An experimental record¹⁷ of an isolated cavity formation at the downstream side of a valve is shown in Fig. 3-22. These data were taken in a 2-in. plastic pipe with 31.3 ft of length downstream of the valve. The wavespeed was measured to be 2070 ft/s, and the initial fluid velocity in this case was 4.58 ft/s. The duration of existence



Figure 3-22 Column separation downstream from valve.

of the first cavity at the valve may be seen to be about 17L/a seconds. The vaporous cavitation model described above was used to model this experiment, and the results are presented in Fig. 3-22. It may be seen that the timing and magnitude of the pressure rise upon collapse of the first cavity are in reasonable agreement. The calculated maximum size of the cavity was about 0.0058 ft³. However, the growth and collapse of the second cavity in experiment and numerical model are clearly not in agreement. The physical measurements indicate considerably more dissipation than the analytical study, and a short-duration pulse appears in the numerical results that is not present in the experimental record.

3-9 Algebraic Method

In many low-friction systems, and in systems with sensitive dynamic boundary conditions that require extremely small time steps, an algebraic representation of the compatibility equations offers appeal. In this procedure the characteristic lines extend more than one reach, generally the full pipe length, but time steps are utilized that are related by integers to L/a seconds. The algebraic equations are also an integral part of the valve stroking developments in Chapter 9.

View Verification Case 10 Model

Verification Case 10

Wylie F	age 69	DVC	Model	case
TJ1				J2
0		P1		÷

View Model Problem Statement

PRODUCT: AFT Impulse 9

TITLE: ImpVerify11.imp

REFERENCE: Efficient Calculation of Transient flow in Simple Pipe Networks, 1992, Journal of Hydraulic Engineering, Vol. 118, No. 7, No. 26648, July, Karney, Bryan W. and McInnis, Duncan, pp. 1022-1030

FLUID: Water

ASSUMPTIONS: Karney uses a relief valve connected to 3 pipes which discharges to atmosphere. AFT Impulse does not support a relief valve with this configuration. Thus an additional pipe (called P8) is used and made as short as possible without increasing pipe sectioning. The valve at J6 is then located at the end of pipe P8, and is modeled with an event transient to simulate Karney's relief valve.

RESULTS:





DISCUSSION:

This model represents the solution for how a network responds to changes in a control valve. Differences between the published results and results from AFT Impulse may be attributed to the differences in how the relief valve is modeled in AFT Impulse, as is discussed in the assumptions above.

Verification Case 11 Problem Statement

Verification Case 11

Efficient Calculation of Transient flow in Simple Pipe Networks, 1992, Journal of Hydraulic Engineering, Vol. 118, No. 7, No. 26648, July, Karney, Bryan W. and McInnis, Duncan, pp. 1022-1030

Karney Title Page

TABLE 4.	Summary	of	Maximum	and	Minimum	Hydraulic	Grade-Line	(HGL)
Elevations								
		_		-				

	Cas	ie 1	Case 2			
Node number (1)	Maximum HGL (m) (2)	Minimum HGL (m) (3)	Maximum HGL (m) (4)	Minimum HGL (m) (5)		
1	200.4	200.0	200.3	199.9		
2	208.7	186.3	208.7	181.8		
3	192.1	186.6	192.1	186.6		
4	175.1	175.0	175.1	175.0		
5	199.6	177.5	199.6	164.6		
6	215.6	181.8	215.6	155.6		
7	275.6	151.9	275.6	80.2		

negative pressure wave. By allowing fluid storage, the reservoirs and surge tank limit the pressure changes at their respective nodes. More detailed information about the system transient response is provided

More detailed information about the system transient response is provided in Figs. 6 and 7. Note the expected correspondence in case 1 and case 2 head and flow traces during the initial period of valve closure. The highpressure waves initiated at node 7 by the closing valve are propagated throughout the system. As the head builds at node 6, the relief valve set point is exceeded at 6 s. When the valve opens, the release of fluid at that location reduces the pressure. The work done in forcing water through the valves at nodes 6 and 7 attenuates the transient and allows the system to reach state quickly.

The behavior of the system changes dramatically as the control valve at node 7 reopens (between 25 and 30 s). The increased demand at node 7 causes a severe drop in the pressure, thus increasing the flow at the node 1 reservoir. In addition, the surge-tank flow reverses and begins to discharge water into the network. Note how slowly the water level in the surge tank changes compared to the rapid pressure fluctuations at node 3. The role of orifice and connector losses, as well the importance of inertial effects, is strongly indicated by these differences (bottom left graphs of Figs. 6 and 7).

7). The preceding remarks are merely intended to convey a sense of how the system reacts to the control-valve operations. This is not, however, the intent of the example. More important are the following points.

1. Five of the seven boundary conditions are explicitly solved by (32) (which also permits connector, tank inertia, and friction terms) in a way tha automatically accounts for flow reversal. Thus, only a single pass through the solution is required. No known reference capitalizes on the explicit nature of the general solution to this entire class of devices. In one reference, nine separately formulation boundary conditions are presented to deal with storage-like boundary conditions. Despite this, not all boundary conditions present in this example network can be solved. Nor do standard references determine the sign of the flow in advance of the solution, except in the simplest of cases.

2. Although the maximum number of pipes at any junction in the example is only three, no restriction on this number is required. Wylie and Streeter (1982) clearly state this fact. Watter's (1984) approach, by contrast, separately

1026



FIG. 6. Hydraulic Grade-Line Elevations and External Flows at Selected Locations: Case 1



FIG. 7. Hydraulic Grade-Line Elevations and External Flows at Selected Locations: Case 2

1027

View Verification Case 11 Model

Verification Case 11



View Model Problem Statement

PRODUCT: AFT Impulse 9

TITLE: ImpVerify12.imp

REFERENCE: Efficient Calculation of Transient flow in Simple Pipe Networks, 1992, Journal of Hydraulic Engineering, Vol. 118, No. 7, No. 26648, July, Karney, Bryan W. and McInnis, Duncan, pp. 1022-1030

FLUID: Water

ASSUMPTIONS: Karney uses a relief valve connected to 3 pipes which discharges to atmosphere. AFT Impulse does not support a relief valve with this configuration. Thus an additional pipe (called P8) is used and made as short as possible without increasing pipe sectioning. The relief valve at J6 is then located at the end of pipe P8.

RESULTS:





DISCUSSION:

This model represents the solution for how a network responds to changes in a control valve. Differences between the published results and results from AFT Impulse may be attributed to the differences in how the relief valve is modeled in AFT Impulse, as is discussed in the assumptions above.

Verification Case 12 Problem Statement

Verification Case 12

Efficient Calculation of Transient flow in Simple Pipe Networks, 1992, Journal of Hydraulic Engineering, Vol. 118, No. 7, No. 26648, July, Karney, Bryan W. and McInnis, Duncan, pp. 1022-1030

Karney Title Page

TABLE 4.	Summary	of	Maximum	and	Minimum	Hydraulic	Grade-Line	(HGL)
Elevations								
	-	-	the second second					

	Cas	ie 1	Case 2		
Node number (1)	Maximum HGL (m) (2)	Minimum HGL (m) (3)	Maximum HGL (m) (4)	Minimum HGL (m) (5)	
1	200.4	200.0	200.3	199.9	
2	208.7	186.3	208.7	181.8	
3	192.1	186.6	192.1	186.6	
4	175.1	175.0	175.1	175.0	
5	199.6	177.5	199.6	164.6	
6	215.6	181.8	215.6	155.6	
7	275.6	151.9	275.6	80.2	

negative pressure wave. By allowing fluid storage, the reservoirs and surge tank limit the pressure changes at their respective nodes. More detailed information about the system transient response is provided

More detailed information about the system transient response is provided in Figs. 6 and 7. Note the expected correspondence in case 1 and case 2 head and flow traces during the initial period of valve closure. The highpressure waves initiated at node 7 by the closing valve are propagated throughout the system. As the head builds at node 6, the relief valve set point is exceeded at 6 s. When the valve opens, the release of fluid at that location reduces the pressure. The work done in forcing water through the valves at nodes 6 and 7 attenuates the transient and allows the system to reach state quickly.

The behavior of the system changes dramatically as the control valve at node 7 reopens (between 25 and 30 s). The increased demand at node 7 causes a severe drop in the pressure, thus increasing the flow at the node 1 reservoir. In addition, the surge-tank flow reverses and begins to discharge water into the network. Note how slowly the water level in the surge tank changes compared to the rapid pressure fluctuations at node 3. The role of orifice and connector losses, as well the importance of inertial effects, is strongly indicated by these differences (bottom left graphs of Figs. 6 and 7).

7). The preceding remarks are merely intended to convey a sense of how the system reacts to the control-valve operations. This is not, however, the intent of the example. More important are the following points.

1. Five of the seven boundary conditions are explicitly solved by (32) (which also permits connector, tank inertia, and friction terms) in a way tha automatically accounts for flow reversal. Thus, only a single pass through the solution is required. No known reference capitalizes on the explicit nature of the general solution to this entire class of devices. In one reference, nine separately formulation boundary conditions are presented to deal with storage-like boundary conditions. Despite this, not all boundary conditions present in this example network can be solved. Nor do standard references determine the sign of the flow in advance of the solution, except in the simplest of cases.

2. Although the maximum number of pipes at any junction in the example is only three, no restriction on this number is required. Wylie and Streeter (1982) clearly state this fact. Watter's (1984) approach, by contrast, separately

1026


FIG. 6. Hydraulic Grade-Line Elevations and External Flows at Selected Locations: Case 1



FIG. 7. Hydraulic Grade-Line Elevations and External Flows at Selected Locations: Case 2

1027

View Verification Case 12 Model

Verification Case 12



Verification Case 13

View Model Problem Statement

PRODUCT: AFT Impulse 9

TITLE: ImpVerify13.imp

REFERENCE: Modern Analysis and Control of Unsteady Flow in Pipelines, 1979, Ann Arbor Science, Watters, Gary Z., PE, Page 181, Ex. 7-2

FLUID: Water

ASSUMPTIONS: N/A

RESULTS:



DISCUSSION:

The AFT Impulse model is built with one pump junction that represents four identical pumps operating in parallel which are simultaneously tripped in order to replicate the problem statement in Watters.

List of All Verification Models

Verification Case 13 Problem Statement

Verification Case 13

Modern Analysis and Control of Unsteady Flow in Pipelines, 1979, Ann Arbor Science, Watters, Gary Z., PE, Page 181, Ex. 7-2

Watters Title Page

PUMPS IN PIPELINES 181

Example 7-2

To illustrate the effects of booster pumps under a power failure situation, the same four pumps of example 7-1 are placed in the interior of a pipeline. The pipeline is 30 inches in diameter, 45,000 feet long and constructed of welded steel. The f-value is 0.0128 and the wave speed is 3590 fps. A profile of the pipeline and the steady state EL-HGL is shown on Figure 7-8.

The booster pump power failure program no. 9 is used to analyze the resulting water hammer. Check valves are installed to prevent backflow and a frictionless forward-flow bypass is activated when the pump head drops to zero with forward flow occurring. The data necessary to run the analysis is shown below and the program listing is given in Figure 7-9.

Minimum and maximum head envelope curves graphically show the range of head fluctuation for a 60 second simulation. Note that high heads on the suction side of the pumps occur as well as low head on the discharge side. No column separation occurs in this case.

DATA



Figure 7-8. Pressure extremes resulting from power failure in a booster pump config

View Verification Case 13 Model

Verification Case 13



Verification Case 14

View Model Problem Statement

PRODUCT: AFT Impulse 9

TITLE: ImpVerify14.imp

REFERENCE: Fluid Transients in Systems, 1993, Prentice-Hall, E. Benjamin Wylie, Victor L. Streeter, Page 153, Ex. 7-1

FLUID: Water

ASSUMPTIONS: Wylie's method includes a combined discharge valve and pump four quadrant element. AFT Impulse does not support this combined element – the pump and valve must be modeled as separate elements. Thus the AFT Impulse model places the valve at the equivalent of one computing station downstream of the pump which is 72 feet. The total pipe length between pipes 1 and 2 is 1440 feet, the same as Wylie.

Because of this, the appropriate location to compare transient head and flow is the inlet of pipe 2, which represents the valve discharge. This data is shown below.

RESULTS:



Pump Discharge HGL vs. Time



DISCUSSION:

The results in Wylie are based on a computer program in Appendix D which assumes that once the flow goes to zero at the pump discharge (this occurs when the valve closes at about 9.5 seconds) then the pump speed stays constant at whatever value it has at that time. This is not a completely valid assumption, and AFT Impulse does not assume this. Thus the pump speeds do not agree as well after this time. The HGL prediction is not impacted because it is downstream of the valve which, once closed, the pump speed can no longer impact.

List of All Verification Models

Verification Case 14 Problem Statement

Verification Case 14

Fluid Transients in Systems, 1993, Prentice-Hall, E. Benjamin Wylie, Victor L. Streeter, Page 153, Ex. 7-1.

Wylie Title Page

Sec. 7-4 Pumping Station with Single Pump

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say 0.0001, τ should be set to zero, which effectively removes the pump from the system in favor of a closed valve.

Example 7-1

The pump in the system in Fig. 7-5 is to be analyzed for a pump failure, including a prescribed valve closure. The pump characteristic curve data for $N_s = 1270$ in Fig. 7-2 are used with $H_R = 310$ ft, $Q_R = 6.3$ ft³/s, $N_R = 1760$ rpm, $T_R = 730$ lb-ft, and $WR_g^2 = 187$ lb-ft². The power is removed from the pump at time zero, and there is a 1.5-s delay before the valve begins to close.



Figure 7-5 Pipeline system for pump failure.

The program to solve this problem, called PUMP, is provided in Fig. D-3a, Appendix D. Four reaches have been used in the pipeline in this example. The loss coefficient for the valve in the fully open position is identified by the variable CK. The prescribed valve motion is defined in the vector TAU with tabular values identified at equal intervals of time, DTAU. One of the first steps in the algorithm is to find the steady operating condition. This requires a simultaneous solution utilizing the pump characteristic head curve and the system characteristics, including the open valve. An estimated dimensionless velocity, VI, is provided in data to begin Newton's method search to find the initial operating point that matches the pump and system characteristics.

Output from the program for a particular specified valve operation is also presented in Fig. D-3b, Appendix D, while pressure, flow, and speed change are shown in Fig. 7-6. It is noted that this particular valve closure is not necessarily optimal in the sense of controlling the transient; it is only an illustration of system behavior. In the output it should be observed that the flow reverses at the pump before the rotational speed reverses, as would be anticipated when pumping against a gravity load. Another system response to observe in the output is the head–discharge relationship at the pump prior to the first reflection from the downstream reservoir. The results produce a straight line whose slope is the pipeline characteristic impedance.



Appendix D Reference Computer Programs								
A. XL. EL. D. F=		3600.0	1440.	0 275.0	1.00	0.02	0	
QR, HR, TR, RN, WRR-		6.3	310.	0 730.0	1760.	0 187.	0	
G, TM, TOL, VI, V=		32.200	12.00	0 .0002	.900	0 1.018	3	
N, KIT, JPR, IGRAF=		4		51		1		
CK, DTA	U, TAU-	.300	.500					
		1.000	1.000	1.000 1	.000	.535 .	070 .065	.060
		.055	.050	.045	.040	.035 .	030 .025	.020
		.015	.010	.005	.000			
TIME	TAU	ALPHA	BETA	v	Q(1)	Q (NS)	H(1)	H(NS)
.000	1.000	1.000	1.001	1.018	6.415	6.415	304.836	275.000
.200	1.000	.879	.775	.932	5.870	6.415	226.601	275.000
.400	1.000	.784	.618	. 872	5.491	6.415	171.095	275.000
.600	1.000	.707	. 504	.829	5.221	5.358	130.346	275.000
. 800	1.000	.645	.418	.798	5.024	4.620	99.721	275.000
1.000	1.000	. 592	. 352	.638	4.022	4.090	101.025	275.000
1.200	1.000	. 548	. 295	. 520	3.279	3.701	95.899	275.000
1.400	1.000	.511	.247	.431	2.718	2.740	88.364	275.000
1.600	. 907	.480	.210	. 364	2.296	1.982	81.152	275.000
1.800	.721	.455	.156	.213	1.345	1.384	79.647	275.000
2.000	. 535	.437	.109	.091	. 574	. 922	75.857	275.000
2.200	. 349	.424	.079	008	047	030	71.713	275.000
2.400	.163	.414	.064	082	519	825	69.823	275.000
2.600	.069	.405	.074	224	-1.414	-1.472	77.619	275.000
2.800	.067	. 392	.119	333	-2.100	-1.951	91.965	275.000
3.000	.065	.3/1	.179	418	-2.636	-2.111	106.075	275.000
3.200	.063	. 343	.231	480	-3.026	-3.347	117.067	275.000
3.400	.061	. 305	. 329	579	-3.649	-3.769	143.227	275.000
3.600	.059	.255	.400	646	-4.0/3	-4.06/	101.030	275.000
3.800	.057	133	. 451	596	-4.605	-4.409	175.214	275.000
4 200	.053	064	537	- 777	-4 804	-4 973	201 218	275.000
4 400	051	- 011	559	- 806	-5 079	-5 118	213 173	275 000
4.600	.049	- 088	564	- 826	-5 202	-5 279	223 362	275 000
4.800	.047	164	.563	837	-5.276	-5.373	232.712	275.000

7.600	.019	775	.034	495	-3.117	-3.138	348.172	275.000
7.800	.017	777	.005	449	-2.832	-2.853	351.345	275.000
8.000	.015	777	018	403	-2.540	-2.562	354.321	275.000
8.200	.013	773	037	356	-2.240	-2.262	357.490	275.000
8.400	.011	766	060	307	-1.932	-1.956	361.036	275.000
8.600	.009	756	089	256	-1.612	-1.641	364.757	275.000
8.800	.007	741	126	203	-1.282	-1.314	369.045	275.000
9.000	.005	721	168	149	938	973	373.769	275.000
9.200	.003	695	214	092	578	617	378.987	275.000
9.400	.001	663	261	032	199	243	384.955	275.000
9.600	.000	663	261	.000	.000	.153	362.697	275.000
9.800	.000	663	261	.000	. 000	. 574	309.532	275.000
10.000	.000	663	261	.000	.000	. 615	253.317	275.000
10.200	.000	663	261	.000	.000	.242	193.473	275.000
10.400	.000	663	261	.000	.000	152	187.491	275.000
10.600	.000	663	261	.000	.000	572	240.528	275.000
10.800	.000	663	261	.000	.000	614	296.644	275.000

HMAX, HMIN	= 38	4.955	.000					

Figure D-3(b) PUMP. FOR (Chapter 7) Output, Example 7-1

View Verification Case 14 Model

Verification Case 14

Pump Trip With Four Quandrant, Wylie Pg. 153, Ex. 7-1



Verification Case 15

View Model Problem Statement

PRODUCT: AFT Impulse 9

TITLE: ImpVerify15.imp

REFERENCE:Fluid Transients in Pipeline, 1988, Nippon Kokan Technical Report, Overseas No. 52, Toshihiko Kamemura, et. al., Page 48, Case B.

FLUID: Water

ASSUMPTIONS: N/A

RESULTS:



Absolute Pressure Head at x = 0m



Absolute Pressure Head at x = 120m





DISCUSSION:

All of the results from Impulse were compared to the measured results plotted in figures 13-17 found in the reference. This was accomplished by scanning the figures, and using digitization software to obtain values for the plotted results.

Figures 13-15 in the reference plot the results as Absolute Pressure Head, whereas Impulse plots pressure head as the Hydraulic Gradeline, which is a relative pressure. In the case of Figure 14, the results

for Hydraulic Gradeline plotted from Impulse had to be adjusted by 4.56 m to match the absolute pressure head due to the change in pipe elevation at x = 40m.

List of All Verification Models

Verification Case 15 Problem Statement

Verification Case 15

Fluid Transients in Pipeline, 1988, Nippon Kokan Technical Report, Overseas No. 52, Toshihiko Kamemura, et. al., Page 48, Case B.

Kamemura Title Page



Fig. 5 Schematic of typical control valve

3.4 Application of SURGE 2

As described in Par. 3.1, the calculation results of SURGE 2 are output graphically, and hence evaluation of analyzed results can be done easily. Also, as the program contains almost all equipment used in the actual pipeline, it can calculate not only maximum or minimum pressure but also analyze sequence and control systems

The following are examples of subjects that can be analyzed:

analyzed. (1) Computation of adequate pump capacity and pipe diameter, by obtaining flow rate and pres-sure balance at each part of the piping system, based on specified boundary condition, piping layout, and kinds of equipment connected to the piping.

In the case a pipeline is operated according to a certain sequence, the calculation of maximum pressure and judgement of negative pressure produced in the pipeline, by following the changes in the pres sure and flow rate in the pipeline with the passage of time

(3) Determination of an optimum operation sequence such as line change, valve stroke, and startup and stop of pumps

Function check of control valves. (4) (5) In the case a pulsation occurs in the flow, presence of resonance in fluid vibration.

Determination of optimum specifications for (6) equipments such as accumlators, surge tanks, surge relievers, and air valves.

(7) Capacity calculation of slop tanks for surge relievers.

(8) Comparison between fluctuation pattern of ressure or flow rate at occurrence of leakage and fluctuation pattern caused by other factors.

Experiment and analysis of liquid 4. column separation phenomenon

4.1 Outline

Analysis method of SURGE 2 follows that of SURGE 1 which has an application record of over ten years, and its reliability can be regarded quite high, with the exception of liquid column separation.

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Therefore, this paper presents the results of experiments and analysis with regard to liquid column separation phenomenon and aims to verify reliability of SURGE 1.

There are not many actual pipeline data regarding liquid column separation phenomenon in the world. Accordingly, in order to obtain data for comprehension and analysis of liquid column separation pheno-menon, fundamental and practicable experiments of liquid column separation were carried out in two kinds of pipelines. These experiments were carried out with the cooperations of the Takenaka and Kitagawa Laboratory, Faculty of Engineering, Tokyo Institute of Technology.

4.2 Test pipelines

The outlines of the test pipelines A and B used in the experiments are shown in Fig. 6 and Fig. 7. Both pipelines are made of transparent acrylic pipe, 200m long, 15.2mm inside diameter. and 5mm wall thick-ness, so that the entire inside of the pipeline can be bess, so that the either instead of the profiles can be observed. The pipeline is built of ten rounds of track, each round beings 20m long, and its downstream end is connected to a reservoir with 0.5m pressure head. However, in test pipeline B, one round of 20m track is vertically raised so that the highest part of the pipe-line reaches 4.56m in height.

The upstream end of the pipeline is connected to a pump and a valve. When water is pumped into the pipeline and the valve at upstream end is instantane-ously closed, transients phenomenon occurs. Initial flow rate and initial pressure at the upstream end were measured by the area flow meter and the Bourdon tube pressure gauge which were inserted immediately in front of the valve at upstream end.





Schematic of test pipeline: case B

NIPPON KOKAN TECHNICAL REPORT Overseas No. 52 (1988)



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Also, pressure and flow rate fluctuations at transients were measured by the semiconductor pressure transducer and the electro-magnetic flow meter and recorded by the electro-magnetic oscillograph.

4.3 Experiments

Experiments were conducted in two cases, case A and case B. Case A used test pipeline A in which the upstream end valve was instantaneously closed to produce liquid column separation immediately behind the valve. Case B used test pipeline B in which the upstream end valve is instantaneously closed to produce liquid column separations immediately behind the valve and at higher location. Experimental conditions are shown in *Table 1*.

Propagation speed of pressure wave was obtained by producing transient phenomenon without accompanying liquid column separation and by recording wave forms.

4.4 Comparison between test results and analysis results

4.4.1 Case A

The state of liquid column separation occurring immediately behind the valve is shown in *Photo 1*, and the test and analysis results in *Fig. 8* to *Fig. 12*. Pressure at x=0 m was dropped to vapor pressure by closing the valve and rarefaction wave was propagated to downstream side, thus causing pressures at

by closing the valve and rarefaction wave was propagated to downstream side, thus causing pressures at other measuring points to be dropped to vapor pressure. Pressure at x = 120 m started to violently oscillate after it had once dropped to vapor pressure. During this period, flow velocity was reduced and the direction of flow reversed. The first re-form occurred in 3.3 seconds after the closure of the valve, and thereafter, separation and re-form were repeated several times and transients phenomenon attenuated.

As can be seen from Fig. 8 to Fig. 12, calculated values and measured values well agree with each other.

4.4.2 Case B

The state of liquid column separation which occurred at high location is shown in *Photo 2*, and the results of experiment and analysis in *Fig. 13* to *Fig. 17*.

Pressure at x=0 m was dropped to vapor pressure by closing the valve and rarefaction wave was propagated to downstream side, thus producing large cavities immediately behind the valve and the high location. Also, flow speed was rapidly reduced with propagation of rarefaction wave. The cavity produced immediately behind the valve collapsed quicker than the one produced at the high location. And, after separation and re-form were repeated four times immediately behind the valve, the vapor cavity at the high location collapsed and re-form pressure generated. As shown in Fig. 13 to Fig. 17, in the first re-form

As shown in Fig. 13 to Fig. 17, in the first re-form at the high location, there are good agreements between the calculated and measured values both in re-form pressure and time. The calculated value thereafter differs somewhat from the experimental value

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Photo 1 Liquid column separation at valve down stream



Photo 2 Liquid column separation at high location

but is sufficient accurate for engineering purpose.

5. Conclusion

The contents of this paper can be summarized as follows:

(1) The program. SURGE 2, which can analyze liquid column separation phenomenon in a pipeline, has been developed by utilizing the characteristics method which introduces released gas dispersion model.

(2) SURGE 2 is a general purpose program which can analyze not only the liquid column separation phenomenon but also any fluid transients phenomenon in a pipeline.

(3) Experiments of liquid column separation were carried out using test pipelines 15.2 mm in diameter and 200 m in length. It was found that the experimental results well agreed with the calculated

NIPPON KOKAN TECHNICAL REPORT Overseas No. 52 (1988)

View Verification Case 15 Model

Verification Case 15



Verification Case 16

View Model Problem Statement

PRODUCT: AFT Impulse 9

TITLE: ImpVerify16.imp

REFERENCE: Waterhammer Analysis, John Parmakian, Dover Publishing, 1963, Page 75 - 86.

FLUID: Unspecified. Specific gravity is 1.155. Viscosity is not relevant because friction factors are assumed. Liquid bulk modulus is not relevant because all wavespeeds are specified.

ASSUMPTIONS: Parmakian assumes the pipes are frictionless. The Impulse model assumes the friction factors are very small (0.001). The specific speed of the example pumps was 0.79 (2160 gpm units). The four quadrant data set from Kittredge of 0.71 (1935 gpm units) was assumed. Neglect cavitation.

From Parmakian's Figure 56 on page 86, it was estimated that the pump discharge elevation was 36 feet and that the pipe traveled horizontally for 1000 feet before rising to the discharge reservoir. It was also estimated that the pipe entered the discharge reservoir at 200 feet.

RESULTS:







DISCUSSION:

Parmakian obtained these results using graphical waterhammer methods.

The specific speed of the example pumps was 0.79 (2160 gpm units). AFT Impulse has a data set from Thorley for exactly this specific speed. But agreement with the predictions was marginal and is not shown. The next closest specific speed of 0.71 (1935 gpm units) gave very good agreement and is shown above. The classic data from Donsky for specific speed of 0.46 (1270 gpm units) was also ran and gave good agreement (but is not shown).

List of All Verification Models

Verification Case 16 Problem Statement

Verification Case 16

Waterhammer Analysis, John Parmakian, Dover Publishing, 1963, Page 75 - 86.

§ 42] WATERHAMMER IN PUMP DISCHARGE LINES

turbine, reaches runaway speed in reverse. As the pump approaches runaway speed, the reverse flow through the pump reduces rapidly, and this reduction in the flow produces a pressure rise at the pump and along the length of the discharge line.

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In order to determine the transient hydraulic conditions at the pump and discharge line subsequent to a power failure at the



46. Graphical waterhammer analysis

Consider the pumping plant installation shown in Figure 54. If a power failure occurs at all three pump motors, $2\rho = 2.31$ and $K_1 = 0.224$. For a time interval $\Delta t = L/4a$,



Figure 54



86 WATERHAMMER IN PUMP DISCHARGE LINES [§ 47

points are shown in Table 5 and the graphical waterhammer solution is completed as shown in Figure 55, from which the following limiting values are read:

Maximum drop in head at pump

 $= 0.92H_0 = 202$ feet.

Maximum drop in head at mid-length of discharge line

 $= 0.69H_0 = 152$ feet.

Maximum head rise at pump

 $= 0.61 H_0 = 134$ feet.

Maximum head rise at mid-length of discharge line

 $= 0.35H_0 = 77$ feet.

A time history of the head, flow, and speed changes as obtained from the graphical solution is shown in Figure 47. 86 WATERHAMMER IN PUMP DISCHARGE LINES [§ 47

points are shown in Table 5 and the graphical waterhammer solution is completed as shown in Figure 55, from which the following limiting values are read:

Maximum drop in head at pump

 $= 0.92H_0 = 202$ feet.

Maximum drop in head at mid-length of discharge line

 $= 0.69H_0 = 152$ feet.

Maximum head rise at pump

 $= 0.61 H_0 = 134$ feet.

Maximum head rise at mid-length of discharge line

$$= 0.35H_0 = 77$$
 feet.

A time history of the head, flow, and speed changes as obtained from the graphical solution is shown in Figure 47.

47. Water column separation

The maximum positive and negative pressure changes obtained from the waterhammer solution are plotted on the discharge line profile in Figure 56 to show the limiting pressures for



Figure 56

§ 48] WATERHAMMER IN PUMP DISCHARGE LINES 87

which the discharge line should be designed. When the minimum pressure at any point along the pump discharge line reaches the vapor pressure of water, the waterhammer solution is no longer valid. If this subatmospheric pressure condition inside the pipe persists for a sufficient period, the liquid water column parts and is separated by a section of vapor. Water column separation sometimes occurs during the initial negative surge waves on long pump discharge lines at high points which are near the hydraulic gradient. Wherever possible, this condition should be avoided by using either a surge tank, air chamber, or larger motor WR^2 because of the high pressure created when the two liquid water columns rejoin. When water column separation cannot be avoided, special means must be taken to minimize the violence of impact due to the rejoining of the water columns. This can be accomplished by positioning special control valves or other protective devices which will either reduce the reverse velocity of the upper column or increase the reverse velocity of the lower water column.

View Verification Case 16 Model

Verification Case 16



Verification Case 17

View Model Problem Statement

PRODUCT: AFT Impulse 9

TITLE: ImpVerify17.imp

REFERENCE: Watters, G.Z., Modern Analysis and Control of Unsteady Flow in Pipelines, Ann Arbor Science Publishers Inc. pp. 170-173, Example 7-1

FLUID: Water

ASSUMPTIONS: Transient cavitation turned off

RESULTS:









DISCUSSION:

Column separation would occur after 5.19 seconds and Watter's model did not account for this so he stopped his model at this point. AFT Impulse can model column separation, but for the purposes of this verification the cavitation capabilities are turned off in the AFT Impulse model. This will result in the warning saying system pressure has gone below vapor pressure.
List of All Verification Models

Verification Case 17 Problem Statement

Verification Case 17

Watters, G.Z., Modern Analysis and Control of Unsteady Flow in Pipelines, Ann Arbor Science Publishers Inc. pp. 170-173, Example 7-1

)

Watters Title Page

170 UNSTEADY FLOW IN PIPELINES

 $H_p/N^2 v_S$, Q/N will be a sequence of straight line segments (see Figure 7-5). The equation of the straight line over the anticipated range of Q/N is

$$\frac{H_{p}}{N^{2}} = \left[\frac{H_{A} \cdot H_{B}}{Q_{A} \cdot Q_{B}} \frac{Q}{N} + H_{B} \cdot Q_{B} \frac{H_{A} \cdot H_{B}}{Q_{A} \cdot Q_{B}}\right] N_{s1} \cdot \dots \cdot (7-28)$$

where Nst is the number of stages for each of the pumps. Condensing this equation to the form

$$\frac{H_{p}}{N^{2}} = \left[C_{\gamma} \frac{Q}{N} + C_{a}\right] N_{st} \qquad (7-29)$$



Figure 7-5. Piecewise linear representation of Hg/N² vs. Q/N values

PUMPS IN PIPELINES 171

we can now combine Equation 7-29 easily with the other appropriate equations. The result of such a combination gives

$$V_{P_{d}} = \frac{\frac{C_{1}}{C_{2}} + N_{st}N^{2}C_{s} + \frac{C_{3}}{C_{4}}}{\frac{1}{C_{4}} + \frac{A_{d}}{C_{2}A_{s}} - \frac{NC_{7}A_{d}N_{st}}{N_{pu}}}$$
 (7-30)

where N_{PU} is the number of pumps in parallel. If V_{P₂} >0, then Equations 7-21 through 7-5 can be used to find the remaining unknowns. In addition, we must check H_P. If H_P <0, then we set H_P = 0 and H_{P₃} = H_P and compute the unknown velocity values from the following equations:

$$V_{P_{d}} = \frac{C_{1}C_{4} + C_{2}C_{3}}{C_{2} + C_{4}\frac{A_{d}}{A_{s}}} \dots (7-31)$$

$$V_{P_{s}} = \frac{A_{d}}{A_{s}} V_{P_{d}} \dots (7-32)$$

The Equations 7-21 and 7-22 can be used to find H_{P_s} and H_{P_d} . If, however, V_{P_1} is negative, then $V_{P_s} = V_{P_d} = 0$ and Equations 7-21 and 7-22 are used to compute H_{P_s} and H_{P_d} . Also we must check Q/N and if we are outside the interval A-B, a new set of coefficients C_7 and C_8 must be computed and the solution process repeated.

Example 7-1

I

Four parallel pumps are to be used to pump approximately 11,000 gpm from a reservoir at elevation 395 feet to a storage reservoir whose surface elevation is 840 feet (see Figure 7-6).

surface elevation is 840 feet (see Figure 7-6). The pump discharge lines are check-valved and manifolded into a single welded steel pipeline 30 inches in diameter. The pipe extends horizontally from the pump station at elevation 415 feet for a distance of 2000 feet. It then slopes upward for a distance of 3 miles to elevation 700 feet. The remaining two miles of pipe are reinforced concrete and it slopes upward to enter the storage reservoir at elevation 810 feet. The f-value and wave speed in the steel pipe are 0.0128 and 3590 fps respectively. For the concrete pipe, these values are 0.0120 and 3486 fps. The pumps are Worthington 15H-277 five-stage turbine pumps with characteristics shown on the following page (Courtesy of the Worthington Pump Corp). The 10 19/32-inch impeller is used. The moment of inertia

Pump Corp). The 10 19/32-inch impeller is used. The moment of inertia

of the rotating hardware and water is estimated to be 475 lb-ft². The consequences of complete pump power failure to the system are to be found in the absence of any surge control devices.

)

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Soluth

Program no. 8 for complete power failure to a source pump configuration is used. A program listing follows in Figure 7-7. The data cards necessary to perform the computer simulation are shown below. A plot of the EL-HGL vs. time up to the point of column

1 PUMPS IN PIPELINES 173

shown below. A plot of the EL-FIGL vs. time up to the point of column separation is shown on Figure 7-6. Column separation occurs at 5 seconds after power failure. Once column separation occurs, the analysis technique is no longer valid and execution of the computer program should be terminated.



Figure 7-6. Pr ure wave propagation as a result of pump power failure.

View Verification Case 17 Model

Verification Case 17



Watters, G.Z., Modern Analysis and Control of Unsteady Flow in Pipelines, Ann Arbor Science Publishers Inc. pp. 170-173, Example 7-1

Verification Case 18

View Model Problem Statement

PRODUCT: AFT Impulse 9

TITLE: ImpVerify18.imp

REFERENCE: M. H. Chaudhry, Applied Hydraulic Transients, 3rd ed. Springer, pp. 102-104, 527-533.

FLUID: Water

ASSUMPTIONS: N/A

RESULTS:









DISCUSSION:

No explicit Cv value is given for the valve, but a head loss at a given flow was provided and a full open Cv of 1716 was calculated. The given valve closure curve was then curve fit to the 4th order and then the max Cv of 1716 was applied to this curve to generate the closing profile used by Impulse.

List of All Verification Models

Verification Case 18 Problem Statement

Verification Case 18

M. H. Chaudhry, Applied Hydraulic Transients, 3rd ed. Springer, pp. 102-104, 527-533.

Chaudhry Title Page

102 3 CHARACTERISTICS AND FINITE-DIFFERENCE METHODS

3-12 Analysis Procedure

In this section, we outline steps for the analysis of transient conditions in a piping system.

The shortest conduit in the system is divided into a number of reaches so that a desired computational time interval, Δt , is obtained. According to Evangelisti [1969], a time interval equal to 1/16 to 1/24 of the transit time, i.e., wave-travel time from one end of the system to the other, should give sufficiently accurate results. We recommend, however, to use this criterion as a rough guide only, and increase or decrease Δt depending upon the rate at which transients are produced.

For the selected-value of Δt , the remaining conduits in the system are divided into equal-length reaches by using the procedure outlined in Section 3-6. If necessary, the wave velocities are adjusted to satisfy Eq. 3-69 so that characteristics pass through the grid points (i.e., $C_N = 1$).

The steady-state discharge and pressure head at all the sections are then computed. The time is now incremented by Δt . The transient conditions at all the interior nodes are computed from Eqs. 3-22 and 3-18, and at the boundaries from the appropriate boundary conditions. The steps for increasing the time by Δt and computing the transient condition are repeated until transient conditions for the required time are computed. The flowchart of Fig. 3-22 shows the computational steps for determining the transient conditions in a series piping system.

To illustrate the above procedure, transient conditions produced by closing the downstream valve in the piping system shown in Fig. 3-23a are determined by using the computer program of Appendix B. The variation of effective valve opening, τ , with time are as shown by the τ -t curve in Fig. 3-23b. Since the valve-closure time is long compared to the wave-transit time in the system, pipe no. 2 is divided into two reaches, thus giving $\Delta t = 0.25$ s. Pipe no. 1 is also divided into two reaches to satisfy Eq. 3-69. The initial steady-state conditions are computed at all sections of pipes 1 and 2. Time is incremented by Δt , and the conditions at the interior sections are determined from Eqs. 3-22 and 3-18.

The boundary conditions for the upstream reservoir (Eqs. 3-28 and 3-29) are used to determine the conditions at the upstream end, and Eqs. 3-47, 3-43, 3-44, and 3-46 are used to determine conditions at the junction of pipes 1 and 2. Seven points on the τ -t curve are stored in the computer, and the values at the intermediate times are interpolated parabolically. The conditions at the value are determined from Eqs. 3-42 and 3-17.

Conditions at $t = \Delta t$ at all sections of the system are now known. These are stored as conditions at the beginning of the next time step. This procedure is repeated until transients for the desired duration are computed. The conditions are printed every second time step by specifying IPRINT = 2.



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Fig. 3-22. Flowchart for a series piping system.

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(b) Valve closure curve

Fig. 3-23. Series piping system.

3-13 Case Study

The computation of transient conditions in the upstream conduits of the Jordan River Redevelopment [Portfors and Chaudhry, 1972 and Chaudhry and Portfors, 1973] British Columbia, Canada, caused by closing the pressure reg3-13 Case Study 105

ulating valve and their comparison with the prototype measurements are discussed in this section.

Figure 3-24 shows the longitudinal section of the upstream conduit, typical cross-sections and the schematic layout of the turbine and the bypass valve. The upstream conduit consists of a tunnel which has a 5.28-km-long, mainly D shaped section; and 82-m-long, 3.96-m-diameter, and 451-m-long, 3.2-m-diameter sections; and a 1.4-km-long penstock, reducing in diameter from 3.2 to 2.7 m. The power plant, primarily used for peaking, has one Francis turbine rated at 154 MW and 265.5-m rated head. To reduce the maximum transient-state pressures, a pressure-regulating valve (PRV) is provided. The rating curve for the PRV, as determined from the prototype tests at the rated head H_r of 265.5 m, is shown in Fig. 3-25.

To compute the transient conditions caused by the opening or closing of PRV, a computer program is developed using the boundary conditions for the PRV derived in this section. (The analysis of transients caused by various turbine operations is discussed in Chapter 5 and the boundary conditions for the simultaneous operation of the PRV and wicket gates are developed in Section 10-6.) Points on the PRV rating curve (Fig. 3-25) are stored in the computer at 20 percent intervals of the valve stroke, and the discharge at the intermediate valve openings is determined by linear interpolation. Assuming the valve characteristics obtained under steady-state operation are valid during the transient state, the PRV discharge under net head H_n is given by the equation

$$Q_v = Q_r \sqrt{\frac{H_n}{H_r}} \tag{3-111}$$

In which $Q_v = \text{PRV}$ discharge under a net head of H_n , and $Q_r = \text{discharge}$ under rated net head H_r , both at valve opening τ . Note that both H_r and H_n are total heads, i.e., $H_n = H_P + Q_v^2/(2gA^2)$, in which A = cross-sectionalarea of the conduit just upstream of the PRV.

To develop the boundary condition for the PRV, Eqs. 3-17 and 3-111 are simultaneously solved. Noting that $Q_P = Q_v$ and eliminating H_n from these equations,

$$Q_P = \frac{-C_{16} + \sqrt{C_{16}^2 + 4C_{15}C_{17}}}{2C_{15}} \tag{3-112}$$

in which

$$C_{15} = 1 - \frac{Q_r^2}{2gH_r A^2}$$

 $C_{16} = \frac{{Q_r}^2}{C_a H_r}$

(3-113)

 $C_{17} = \frac{Q_r{}^2 C_p}{C_a H_r} \label{eq:C17}$ Now H_P may be determined from Eq. 3-17.

				I DIVING	on onoon	on m	
VALVE C	PERAT	ION TI	ME = 6.0	0 S			
TIME	INTER	VAL FC	R STORING	TAU CURV	TE = 1.000	S	
VALVE	LOSS	= 60.	05 M FOR	QS = 1.00	00 M3/S		
STORE	ED TAU	VALUE	s:				
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PIPE	NO	LENG	TH DI	A WAY	VE VEL.	FRIC F	ACTOR
		(M)	(M)	(M/S)		
1		550	.0.7	5 11	.00.0		010
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1 11.117	INO	NO	(1)	(N+1)	(1)	(MJ/3)	
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	. 902	2	65 78	63.46	1.000	1.000	
1 0	900	2	67 70	60 72	1.000	. 909	
1.0	. 900	2	69.73	60.75	1.000	. 900	
1 5	012	2	67.70	74 16	. 900	.970	
1.5	.013	1	24.16	74.10	.9//	.907	
2.0	700	2	74.10	79.88	.907	.937	
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2 5	400	2	94.90	125.15	. / 55	. 122	
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4.0	200	2	59.19	104 41	.033	.009	
4.0	. 500	2	104 41	140.41	. 506	.490	
4 5	200	2	67 70	149.14	.490	. 473	
4.5	.200	2	108 47	158 61	344	325	
5.0	100	2	67 70	111 20	103	. 323	
5.0	.100	2	111 20	165 65	.103	166	
5 5	039	1	67 70	113 07	006	.100	
5.5	.030	2	113.07	149.46	.000	.004	
6.0	.000	1	67.70	96.01	-,175	- 106	
0.0	.000	2	96.01	114 27	- 106	.100	
6.5	.000	1	67.70	63.25	- 217	- 157	
0.5		2	63.25	61,79	157		
7.0	.000	1	67.70	34.25	- 139	- 085	
		2	34.25	12.33	085	.000	
7.5	.000	1	67.70	23.55	.047	.035	
		2	23.55	6.74	.035	.000	
8.0	.000	1	67.70	47,63	.208	126	
0.0	.000	2	47.63	34.76	.126	.000	
8.5	.000	1	67 70	82 89	205	1/2	
0.5	.000	2	82 89	88 45	148	.140	
9.0	000	1	67 70	105 95	. 140	.000	
9.0	.000	2	105 95	130 93	.000	.004	
9 5	000	1	67 70	108 02	- 097	- 071	
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10.0	111111		6 / / ()	78 30		- 1 2 2 2 2	

		B-3 Prog	ram Output 533
PIPE NO	SECTION NO	MAX PRESS.	MIN. PRESS.
1 1 2 2 2	1 2 3 1 2 3	67.70 91.18 113.07 113.07 140.26 165.65	67.70 44.05 23.55 23.55 9.53 5.40

View Verification Case 18 Model

Verification Case 18



M. H. Chaudhry, Applied Hydraulic Transients, 3rd ed. New York: Springer, pp. 102-104, 527-533. Series Piping System.

Verification Case 19

View Model Problem Statement

PRODUCT: AFT Impulse 9

TITLE: ImpVerify19.imp

REFERENCE: Kaplan M., Streeter V., and Wylie E.B., Oil Pipeline Transients, The University of Michigan, Industry Program of the College of Engineering, August 1966, IP-743, Long Pipeline.

FLUID: Oil

ASSUMPTIONS: Fluid properties where assumed for crude oil.

RESULTS:











DISCUSSION:

This example demonstrates line pack as the result of closing a valve at the end of a long pipeline. List of All Verification Models

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Verification Case 19 Problem Statement

Verification Case 19

Kaplan M., Streeter V., and Wylie E.B., Oil Pipeline Transients, The University of Michigan, Industry Program of the College of Engineering, August 1966, IP-743, Long Pipeline.

Kaplan Title Page

-9-

at the wave front is shown as a dashed line in Fig. 4 and is seen to approach the original hydraulic gradeline asymptotically in the infinitely long line. In most practical situations a reflection of the attenuated wave occurs at the upstream boundary, although in the relatively long pipeline the reflected wave may be so small as to be undetected. Even after the locus of the head rise has become coincident with the orignal hydraulic gradeline the new gradeline continues to rise, gradually reducing the forward velocity to zero in the pipeline.

It is of interest to note that the attenuation described above does not directly result from frictional effects but arises out of the fact that momentum conditions must be satisfied at the wave front. Without frictional effects in the system, however, the hydraulic gradeline would be horizontal and the phenomena of line packing and attenuation would not exist.

The characteristic's method of solution of the differential equations that describe unsteady flow in a long pipeline automatically includes these newly defined effects since the complete equations are solved. Figure 5 shows the computer results of a sudden valve closure on a long pipeline, as obtained by solution of the transient flow equations for a simple pipe 125 miles long and 30 inches in diameter. The initial steady state velocity was 4.25 ft/sec and the wave speed was 3300 ft/sec. The solid lines show the original hydraulic gradeline and the gradeline at various times after valve closure. At 200 seconds after valve closure the attenuated wave reaches the upstream boundary and is reflected. The dashed lines indicate the extent of the pipeline influenced by the reflected wave as the gradeline continues to rise. At 9 minutes -10-

after valve closure the hydraulic gradeline has reached its maximum level and the forward velocity has been reduced to zero. The adverse gradeline produces flow in the opposite direction. The surging condition continues until friction losses in the system cause the flow to come to rest. In Fig. 5 the line indicated by dots shows the magnitude of the initial wave front as it moves into the undisturbed flow. The attenuation of the wave front is evident.

The superposition of one transient pressure upon another is known as the <u>pyramidal effect</u>. For example, if line packing has occurred due to closure of a valve, then the head is increased upstream by starting of a pumping station, one transient is superposed on another transient.

<u>Rarefaction control</u>⁵ is the opposite of pyramidal effect in that a negative surge wave is generated upstream by shutting down a pump or closing a valve. When this meets a surge wave being transmitted up the hydraulic gradeline they tend to partially cancel the head changes.

These latter two effects are easily demonstrated in a computer solution by proper adjustment of the boundary conditions.

Properties of Fluids. Wave-Speed Determination. Frictional Effects

Viscosity, bulk modulus of elasticity, and density are the important fluid properties needed to design for transient control of long pipelines. Viscosity is a function of temperature primarily, but the bulk modulus of elasticity of oils depends upon both temperature and pressure in some cases.

 [&]quot;Transient Pressures in Long Pipelines," by R. R. Burnett. A.P.I. Annual Pipeline Conference, Division of Transportation, April, 1960.



Figure 5. Results of Computer Solution of Valve Closure on Long Pipeline.

View Verification Case 19 Model

Verification Case 19

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	-	9

Kaplan M., Streeter V., and Wylie E.B., Oil Pipeline Transients, The University of Michigan, Industry Program of the College of Engineering, August 1966, IP-743, Long Pipeline

Verification Case 20

View Model Problem Statement

PRODUCT: AFT Impulse 9

TITLE: ImpVerify20.imp

REFERENCE: Karney, Bryan W and McInnis, Duncan, Transient Analysis of Water Distribution Systems, Journal AWWA, July 1990, pp. 62-70, Figures 2 and 3

FLUID: Water

ASSUMPTIONS: N/A

RESULTS:







DISCUSSION:

The valve Cv is not given, but was calculated based on flow and pressure drop.

List of All Verification Models

Verification Case 20 Problem Statement

Verification Case 20

Karney, Bryan W and McInnis, Duncan, Transient Analysis of Water Distribution Systems, Journal AWWA, July 1990, pp. 62-70, Figures 2 and 3

Karney Title Page

devices can lead to the most severe transient problems. Yet such issues are central to system design and operation. This article emphasizes that the de-

This article emphasizes that the details of how a hydraulic system is modeled or represented can have a critical impact on the predicted transient conditions. Examples illustrate the following three points: (1) in some pipeline systems, the maximum transient pressure is quite sensitive to the assumed initial steady-state velocity; (2) transient conditions may sometimes be more severe in branched or looped systems than in simple series pipelines; and (3) oversizing surge-suppression equipment such as relief valves may degrade a system's transient response. The key result is that transient phenomena in a pipeline system can be both surprising and dramatic. Because of the complexity of system response, the transient analyst must learn to think fundamentally and analyze comprehensively.

Transient analysis and design

Unfortunately, transient analysis is not easy. The governing equations describing the flow are of the nonlinear partial differential variety, the hydraulic devices are complex and data on their performance are difficult to obtain, and the pipeline systems themselves are subject to a host of operating conditions and requirements. To make matters worse, the physical character of the pulse wave propagation is frequently hard to visualize or interpret even for the analyst accustomed to transient phenomena.

ize or interpret even for the analyst accustomed to transient phenomena. The complexity of transient phenomena has, at times, induced many analysts to adopt simplified design procedures. The analysis of hydraulic systems is often facilitated in two primary ways: (1) complex components and other complications in the physical system itself may be ignored, or (2) the range of operating and loading conditions to which the system is subjected is greatly reduced. These simplifications are rationalized on the grounds of necessity (the actual physical system cannot be analyzed) and conservatism (the analyzed system performs worse than the real one). Unfortunately, the assumption that some rudimentary and conservative system can be found is questionable. It is difficult to simplify a pipeline system to ensure worst-case performance under all transient conditions, particularly if the simplifications are made before any analysis has been performed.

Traditional wisdom for identifying worst-case scenarios is based on elementary equations, rules of thumb, or common sense; in other words, simple relations that may have little or no bearing on the performance of more complex systems. Several of the most common of these ideas are presented in this article along with counterexamples

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View Verification Case 20 Model

Verification Case 20



Karney, Bryan W and McInnis, Duncan, Transient Analysis of Water Distribution Systems, Journal AWWA, July 1990, pp. 62-70, Figures 2 and 3

Verification Case 21

View Model Problem Statement

PRODUCT: AFT Impulse 9

TITLE: ImpVerify21.imp

REFERENCE: Karney, Bryan W and McInnis, Duncan, Transient Analysis of Water Distribution Systems, Journal AWWA, July 1990, pp. 62-70, Figures 5 - 7

FLUID: Water

ASSUMPTIONS: Valve Cv is unknown, but calculated based on flow and pressure drop.

RESULTS:





DISCUSSION:

Karney uses very few sections, using fewer in AFT Impulse will result in more similar results to Karney, but using more sections is required to get a better description of the square wave behavior that results from an instantaneous closure.

List of All Verification Models

Verification Case 21 Problem Statement

Verification Case 21

Karney, Bryan W and McInnis, Duncan, Transient Analysis of Water Distribution Systems, Journal AWWA, July 1990, pp. 62-70, Figures 5 - 7

Karney Title Page



Figure 5. Plan sketch, parameter values, and three-dimensional response surface for instantaneous downstream valve closure in a simple series pipeline

any movement of the piston, no matter how slowly accomplished, will be accompanied by changes in fluid density, conduit dimension, and pressure. Even though the resulting changes in density and dimension are typically small, the changes in fluid pressure can be large and cannot be neglected. The connections between this simple

The connections between this simple static compression test and a pipeline transporting fluid are easily made. If the actual conduit length in the static case is taken to be the final value of 1,000 m, what this pipe experiences during the compression can be though tof as a mass imbalance. That is, more fluid is forced to enter the conduit than was originally contained within it. Whenever such an imbalance occurs, compressibility effects must play a role. Thus, whenever flow conditions in a pipeline result in more fluid entering one end than is leaving the other, large pressure changes can be expected. In addition, the greater the mass imbalance, the more severe the

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resulting pressure changes tend to be. In anticipation of ideas to be broached subsequently, it could be suggested that mass imbalance constitutes a more natural and theoretically satisfying criterion for the severity of a system's transient response than does fluid velocity.

Velocity. The origin of transient conditions. The connections between fluid properties (density and compressibility) on the one hand and the law of mass conservation on the other are fundamental to an understanding of fluid transients. Suppose, for example, an adjustment is made to a valve at the downstream end of a pipeline carrying fluid at some initial velocity (Figure 2). For simplicity, it is assumed that the valve is suddenly closed. The valve, of course, can only act locally—it specifies a relationship between flow through the valve and the head loss across the valve. In this case, the discharge and velocity of the fluid at the valve become zero the instant the valve is shut. However, in order for the fluid mass as a whole to be stopped, a decelerating force sufficient to eliminate the substantial 10% kg m/s of momentum must be applied. The only way to provide the required decelerating force is to compress the fluid, thereby generating an increase in pressure large enough to arrest the fluid flow. Because water is heavy, the required force is large; but because water is only slightly compressible, the wave or disturbance will travel quickly. In a system like the one shown, a pressure wave of approximately 100 m would propagate along the pipeline at roughly 1,000 m/s.

In many ways, this system is typical. Closed-conduit systems frequently carry huge amounts of momentum and kinetic energy, and, in addition, hydraulic conditions are in an almost continual state of change. For such systems, the only available mechanism for controlling or changing the flow conditions is shock wave propagation resulting from fluid and pipeline elasticity. Only if the changes in flow rate take place gradually, such that the mass imbalance in the line is always small, is it possible to go smoothly from one steady condition to another. Under these circumstances, no large fluctuations in pressure head or velocity occur, because the pipeline is always near a state of equilibrium.*

always near a state of equilibrium.* If rapid changes occur, whether caused by standard operating procedures or accidental events, a relatively large mass imbalance may arise. The associated pressure pulses are of great magnitude and are capable of bursting or damaging pipelines. In order to model or predict these rapid transient phenomena, complete equations of motion need to be written and solved, both for the pipeline and for all the devices used to control the flow. Standard texts such as those by Wylie and Streeter¹ and Chaudhry² provide the details. The more complete mathematical description should not, however, detract from fundamental insights. Transient conditions arise from local disturbance. This mass imbalance then acts through the combined effects of fluid and pipeline elasticity to accelerate the flow and, ultimately, create a new steady state.

mately, create a new steady state. Special devices that are designed to control or eliminate transient effects should be viewed with caution. It is the physical nature of the control problem that dictates that transient conditions must occur and that frequently deter-

*Even in cases such as this, however, the actual mechanism for maintaining equilibrium in the pipe is still mass imbalance and compressibility effects. The only difference is that the pressure waves are much smaller in magnitude and travel quickly relative to the changes that occur at the ends of the conduit. In such applications, it is often justified to incompressible. Neglecting fluid compressibility leads to be to called "rigid water column" model.

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mines how dramatic transient conditions will be. Often, as in other areas of engineering, no design is superior from all points of view. Instead, there may be compromises that trade off a degree of control under some circumstances for less control under others.

Transient folklore

Much traditional "wisdom" has evolved over time on how to cope with the intricacies of transient phenomena. evolved over time on how to cope with the intricacies of transient phenomena. This wisdom often pertains to design assumptions that simplify the analyst's task by restricting the number and complexity of transient cases that need to be analyzed or specified. In light of modern computer power, however, the rationale for these assumptions needs to be questioned. Indeed, many of the a priori design assumptions are so mis-leading and so frequently false that they should not be regarded as rational design credited transient folklore. In this article, several of these mis-conceptions are addressed, and, by mcans of counterexamples, their potential for erroneous application becomes clear.* To avoid misleading the reader, the title of each topic is stated as the converse of the often improperly understood and applied design axiom. The three most widely revered axioms of transient folklore probably are:

of transient folklore probably are: • maximum steady-state velocities (flows) produce maximum transient head

(hows) product inter-change,
 networks fare better (i.e., looped or branched configurations alleviate water

branched coninguations and viate water hammer), and • if one surge-protection device is good, then two (or more) are better. The examples that follow were not difficult to find, nor have they been substantially altered to make the results of the offer more than the offer more than the results. substantially altered to linke the results contradict the aforementioned notions. They simply demonstrate that there are important cases for which these guide-lines are either false or, at the very least, misleading. Like much of what is called folklore in other screet the previously stated tran-

other areas, the previously stated tran-sient rules have some basis in fact. For example, the origin of the first two rules can be traced to the famous fundamental can be traced to the families fundamental equation of water hammer, which is also called the Joukowski relation. This relation equates changes in head (ΔH) in a pipe to the associated changes in fluid velocity (ΔV) :

 $\Delta H = \pm (a/g) \Delta V$

(1)

in which *a* is the wave speed and *g* is the acceleration resulting from gravity. Clearly this equation implies that the

*All of the transient simulations presented here were produced using $T_p A_N S A M$ (acronym for Transient Analysis Model), which is a proprietary software product of HydraTek Associates, Toronto, Ont., Canada.

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Figure 7. Variation in pressure head at the valve end for a simple series pipeline and a looped network

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View Verification Case 21 Model

Verification Case 21



Karney, Bryan W and McInnis, Duncan, Transient Analysis of Water Distribution Systems, Journal AWWA, July 1990, pp. 62-70, Figures 5 -7

Verification Case 22

View Model Problem Statement

PRODUCT: AFT Impulse 9

TITLE: ImpVerify22.imp

REFERENCE: Liou, Jim C. P., Understanding Line Packing in Frictional Water Hammer, ASME, Journal of Fluids Engineering, August 2016, Vol. 138, Application Example

FLUID: Oil

ASSUMPTIONS: Closure is started at 20 seconds in both cases. Liou states valve Cv vs. time is known, but no curve is provided. It is assumed the valves close linearly over 60 or 180 seconds.

RESULTS:





DISCUSSION:

Liou states "Since the valve head loss is negligible relative to the pipe frictional head loss, the effective valve closure time is much shorter than the physical closure times. Therefore, an instantaneous closure of this valve can be assumed". This is essentially correct as an instantaneous closure results in essentially the same maximum head as the longer closure profiles. This is typically true for long pipelines with long communication times and insignificant valve head loss. Cv profiles should not be considered negligible if the closure time is greater than communication time or if the valve has significant head loss compared to pipe friction (major losses).

List of All Verification Models

Verification Case 22 Problem Statement

Verification Case 22

Liou, Jim C. P., Understanding Line Packing in Frictional Water Hammer, ASME, Journal of Fluids Engineering, August 2016, Vol. 138, Application Example

Liou Title Page



Fig. 8 Comparison between analytical (solid line) and numeri-cal (dashed line) head at the valve after its sudden closure

It is seen that within the range of R of interest, the linear profile is a good approximation, especially for lower R. With this approximation,

$$\int_{-\infty}^{d} (U(T'))^2 dT' = V^2(T) \frac{T}{3}$$
(24)

Using Eq. (20) for V_b , Eq. (21) for H_b , Eq. (24) for the integral, and setting V_d to zero, H_d can be solved from Eq. (22). After simplification, and denoting H_d as $H_V(2T)$, it can be established that sim

$$\frac{H_{\nu}(2T)}{(\Delta H)_0} = 1 + RT \left(1 - \frac{1}{3} \tanh^2 \left(\frac{RT}{2} \right) \right) \quad \text{for} \quad 0 \le T \le 1 \quad (23)$$

Figure 8 compares the head at the closed valve from Eq. (25) with the results from numerical simulations between 0 and 2L/a s. It is seen that Eq. (25) yields a close approximation to the head rise at the closed valve.

the closed valve. It should be noted, because no assumption was made on how U vary along the C⁺ characteristics, a valid numerical simulation can produce more accurate results than Eq. (25) can. Thus, Eq. (25) is not an alternative to a valid numerical simulation. However, Fig. 8 demonstrates that Eq. (25) is an option to quickly and directly compute the head rise at the valve with acceptable accuracy

Accuracy of the Analytical Solution for Line Packing

Accuracy of the Analytical solution for Line Facking Accurate numerical simulations to Eqs. (3) and (4) for the instantaneous valve closure transients were used to evaluate the accuracy of Eq. (25) and, separately, the strain energy approxima-tion. For each R, subtract (ΔH_0) form the simulated head at the valve at 2L/a s and denote the result by W. The subtraction is needed because (ΔH_0) is a part of the simulated head at the valve but not a part of line packing. The % error of line packing at T = 1from Eq. (25) is defined as

$$\% \operatorname{error} = \frac{\left(H_v(2) - (\Delta H)_0\right) - W}{W} \cdot 100$$

The % error for the strain energy approximation is defined in a imilar fashi

error strain energy =
$$\frac{\frac{1}{\sqrt{2}}\frac{fLV_0^2}{D2g} - W}{W} \cdot 100$$
 (27)

Journal of Fluids Engineering

%



Fig. 9 The error of line packing estimation using Eq. (25) (top panel) and using the strain energy approximation (bottom panel)

Figure 9 shows the errors. The maximum error for Eq. (25) occurs at R = 2.25 where the line pack is underestimated by 1.55%. The error is negligible for small *R*. Equation (25) is quite an improvement of the strain energy approximation. The latter significantly underestimates the line packing.

Application Example

The example below shows how to apply Eq. (25). It also indicates the reasonableness of using an instantaneous value closure to approximate valve closures with finite physical closure time for pipelines where the initial steady-state frictional head loss far exceeds the valve head loss prior to its closure. This is often the case for cross-country oil pipelines.

case for cross-country oil pipelines. A 591 mm inside diameter pipe with a length of 80 km trans-ports oil from a source tank with a fixed head to a delivery tank at 0 m of head. The pipeline system has a water hammer wave speed of 1150 m/s. At the discharge end of the pipeline is a motor oper-ated control valve. The valve is a full-ported ball valve with a flow coefficient of 88,900 gpm at 100% stroke (i.e., wide open). The isobaret unlose observation is do no coefficient waves for the source of th The inherent valve characteristic (the flow coefficient versus % stroke curve) is known and used in the simulations described

Prior to its closure, the control valve is wide open, the velocity Prior to its closure, the control valve is wide open, the velocity is 1.82 m/s, and the corresponding Darcy–Weisbach friction factor is 0.018. The control is closed with a constant motor speed in 60 and, separately, in 180 s. (Note that the round-trip travel time for water hammer waves is 2L/a or 139 s. Thus these closure times are not very fast.) For both cases, the valve closure starts at 20 s. What are the maximum heads just upstream of the control valve? With the given data, the pipeline frictional head loss at the ini-tial steady state is 411 m and the head loss through the wide-open valve is 0.006 m. This valve head loss is small but realistic. Since the valve head loss is negligible relative to the pipe firctional head loss, the effective valve closure time is much shorter than the physical closure times. Therefore, an instananeous closure of this

aloss, the elective valve closure time is much solution that the physical closure times. Therefore, an instantaneous closure of this valve can be assumed. This simplifies the problem considerably because the valve characteristics become irrelevant. Using Eq. (5) with $\Delta V = -V_0 = -1.82 \text{ m/s}$, $(\Delta H)_0 = 213.2 \text{ m}$. Using Eq. (18), R = 1.228. With these values and using T = 1, Eq. (25) gives a maximum head of 547.9 m.

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(26)



Fig. 10 The maximum head at the valve computed from Eq. (25) and the simulated head traces at the valve for 60 and Eq. (25) and 180 s closure

This maximum head is compared with the peaks of the simulated head traces at the valve in Fig. 10. The maximum head, which is based on an instantaneous valve closure, matches the simulated peak head for the 60-s valve closure very closely. The maximum head only slightly overpredicted the simulated peak head for the 180-s valve closure despite the physical valve closure time is longer than 2La (139 s) second of the pipeline.

Summary and Conclusion

Summary and Conclusion This study establishes the analytical solution for the attenuated front of velocity and head waves propagating upstream during the La s after a sudden valve closure. It also presents an analytical approximation to the head rise at the closed valve during the 2Las after the valve closure. The accuracy of the approximation is demonstrated. An example illustrates its usage to transients resulted from a discharge valve closure over different times, Although line packing is quantifiable by numerical simulations, the analytical solutions contribute to the understanding of the line packing phenomenon, and offer a simple and direct way to accu-rately compute the maximum pressure due to line packing without resorting to numerical methods or commercial numerical simula-tion software. tion software.

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Nomenclature

- = water hammer wave speed
- $\begin{array}{l} a = \text{water hammer wave speed} \\ D = \text{pipe diameter} \\ f = \text{Darcy-Weisbach friction factor} \\ g = \text{gravitational acceleration} \\ H = \text{head} \\ H_S = \text{steady state head} \\ H_U = \text{head at the supply reservoir} \\ H_V = \text{head at the valve} \\ I_V = \text{bead at the valve} \\ I_V = \text{bigen at the valve} \end{array}$

- L = pipe lengthR = friction coefficient

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t = timeT = dimensionless time

- T = dimensionless time T' = dimensionless time between T and 2T V = discharge velocity $V_0 = steady state discharge velocity$ W = accurately simulated line packing at 2L/a s x = distance from the reservoir toward the valve
- ΔH = amplitude of the head wave front $H)_0 = (a/g)V_0$ ΔV = amplitude of the velocity wave front $(\Delta H$

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