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State-of-the-Art Review of Pressure Surge Studies

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SUMMARY The paper concentrates on reviewing the more recent developments in the analysis, control and suppression of pressure surge phenomena. Reference is made to the impact of digital computers, and to the study of viscous effects, wave speeds, cavitation and column separation, pumps and numerous other boundary conditions relevant to surge investigations. The inclusion of comments on approximate methods should be useful to practising engineers, and the paper is concluded with some suggestions for future lines of research.

NOTATION

A	duct cross-sectional area
D	diameter of a circular section duct
$f(t)$	time-dependent friction factor
H_s	static head
L	pipe length
n	non-dimensional rotational speed
p	pressure
q	non-dimensional volumetric flow rate
R_e	Reynolds number
v	velocity
U_o	initial steady flow velocity
$\forall$	volume of air vessel
y_1, y_2, y_3	see equation (1)
ρ	fluid density
θ	defined by equation (2)

1 INTRODUCTION

The study of pressure surge phenomena, or water hammer, has made considerable strides since the early work of Korteweg, Joukowsky and Allievi, etc. (1-16), at one time the preserve of hydro-power and water supply engineers, pressure surge investigations are now interdisciplinary in nature, involving not only fluid dynamicists but nuclear, chemical and process engineers, stress analysts, physicists, vibration specialists and mathematicians. The computer has almost replaced the drawing board, and the design engineer has available to him literally hundreds of technical papers on the subject (over 400 relevant papers have recently been reviewed (5)).

2 ANALYTICAL DEVELOPMENTS

The numerical method of characteristics has proved most attractive to pipeline designers because for application to transients in liquids, the calculations for pressures and flows in a pipeline normally only involve the solution of a pair of simultaneous equations. Many applications have been reported (17, 18) and cover such diverse fields as the simulation of aircraft fuel systems (19), pumped storage projects (20), cooling water systems for thermal power plants (21), trains in tunnels (22), and liquid-metal-cooled fast breeder reactors (23).

2.1 Viscous Effects

The commonest and simplest approximation for viscous losses is to assume that they are proportional to the flow velocity raised to some power (usually 2) and multiplied by a D'Arcy or Fanning friction factor based on the initial steady flow Reynolds Number. If desired, the friction factor can be revised at each stage of the calculations by recalculating the Reynolds number and having the Moody friction curves stored in the computer in a suitable fashion (16).

A further refinement is to take into account the previous velocity history of the flow in order to determine an appropriate friction loss (24). This aspect has been studied mainly in connection with laminar flows but Trikha (25) suggested that a time dependent friction factor for turbulent may take the form

$$f(t) = \frac{0.316}{R_e^{1/4}} \frac{\rho V^2}{2D} + \frac{16\rho V}{D^2}(y_1 + y_2 + y_3) \qquad (1)$$

in which y_1, y_2 and y_3 are functions of past velocity changes and the other symbols have their usual meanings.

2.2 Speed of Propagation of Pressure Waves

For the majority of surge analyses the long established relationships for wave speeds are usually still quite adequate (26-28). Common sources of variation between actual and theoretical wave speeds are seasonal or operational variations in the liquid compressibility - a few gas bubbles for example could halve the wave speed (27) (28).

When predicting wave speeds in plastic and visco-elastic pipes it is important that the correct value for the elastic modulus of the wall material be used, as this parameter is sensitive to both temperature and rate of strain.

Some engineering applications require the use of flow cross-sectional shapes other than circular, e.g. square, hexagonal and octagonal pipes (30).

The basic equations of unsteady flow retain the same general form, but the terms representing friction losses and wave speed must be modified accordingly.

It is usually assumed that the celerity of pressure waves through liquids contained in slightly elastic ducts is constant. For most practical surge problems this is a reasonable assumption, although it has been demonstrated (31, 32) that even in a 'pure liquid' the effects of bending and of the radial inertia of the duct wall cause a small amount of dispersion of the wave front to occur.

3 COLUMN SEPARATION, CAVITATION AND TWO-PHASE MIXTURES

Simple cases of column separation could be included in the graphical types of analysis, but computer-aided solutions can acknowledge movable and multiple cavities, and also variable wave speeds such as occur in bubbly mixtures. These solutions are still based on several assumptions and simplifications and yet are inevitably complex. So much so that the 1960's marked the emergence of two main lines of development of the means of analysing transient low pressure phenomena. On the one hand there are those (33-38) who have attempted to define solutions for situations in which discrete cavities form, incorporating schemes for the mechanism of gas release, etc. and assuming that the cavity, whilst it exists, may be regarded as a common boundary condition, which may be analysed by conventional theory.

Meanwhile, back in the laboratory, other attempts have been, and still are being, made to study systems in which there is an axial distribution of free gas (27, 28, 39-42). Attention has been focussed, for example, on such features as the mechanism of gas release from, and diffusion in, the liquid phase, heat transfer and surface tension effects,dispersion and attenuation of pressure waves,and the development of suitable numerical methods of solution which, amongst other things, do not become unstable when shock waves develop.

4 HYDRAULIC MACHINERY : PUMPS

The main difficulty when a pump is a boundary condition is the proper representation of its behaviour under transient conditions (44-46). Information on their performance characteristics is usually limited to the normal zone of operation under steady flow conditions. If one accepts that these are valid under transient conditions (and at present there is no alternative) this situation is not too serious if a non-return valve is fitted near to the pump discharge, as this will prevent any significant reverse flow.

One of the major difficulties with pumps is that the non-dimensional forms of the performance characteristics tend towards infinite values for certain flow conditions of interest. Suter (47, 48) overcame this difficulty by introducing a new variable,

$$\theta = \tan^{-1}(n/q) \quad (2)$$

where n and q represent non-dimensional speed and flow respectively. Since all zones of pump operation lie in the interval, $0 < \theta < 2\pi$, by plotting a convenient form of non-dimensional head and torque against θ, a single characteristic for each is obtained.

5 SURGE SUPPRESSION AND CONTROL

Methods of surge suppression and control are based primarily on the principle of reducing the rate at which flow changes occur. The more common methods include the use of surge shafts, air vessels and accumulators, increased pump intertia, slower valve or gate operation, air admission valves, pressure relief valves and by-pass valves.

Some of these methods have attracted a considerable amount of study. Surge tanks, for example, are one of the earliest methods of surge suppression. Initially of very simple design there are now several variations (17, 18, 49, 50, 51).

Air vessels and accumulators tend primarily to be associated with pumping lines and the history of their development is almost as long as that of surge tanks. (9, 10, 17, 18, 52).

Experience, common sense and/or intuition guided early engineers into the use of relief valves for surge protection. They do not now appear to be extensively used on large scale systems except for a recent example (54) where they are protecting a long penstock on a hydro-electric plant in Tasmania.

Control valves have normally been regarded as the cause of many pressure surge problems, and apart from Knapp's paper (55) at the 1937 ASME Symposium the idea of so operating such a valve as to limit the amplitude of the transient pressure wave did not receive serious attention until about the 1950's.

Most common valves produce a highly non-linear flow reduction for a linear rate of valve spindle movement resulting in an almost negligible change of flow for the first 70% or so of closure. As a simple expedient to achieve an approximation to a linear change of flow rate (desirable in the interests of surge control) a two-stage mode of valve closure is sometimes used on prototype systems. Much more sophisticated arrangements have been developed on laboratory sized schemes (16, 56-58), using electro-hydraulic servo-systems to control pressures on both the upstream and downstream sides of a closing valve.

It is usually necessary to utilize one or more of the above methods of surge protection on prototype systems, especially if the pipelines are relatively long. However, for shorter systems containing pumps, a common solution still is to increase the inertia of the rotating parts with a flywheel. Pipes of non-circular section can be advantageous due to the reduction in wave speed compared with that in circular section ducts having similar cross-sectional areas. Flexible hoses also give rise to much lower wave speeds and the visco-eleastic properties of plastic materials enhance the rate of attenuation of transient pressure waves, although they are susceptible to fatigue failures.

6 OTHER ASPECTS OF TRANSIENT PRESSURE WAVES IN CONDUITS

Most of the research into pressure surge phenomena has been directed towards a better understanding of their behaviour for the purposes of improving the design and protection of hydro-power plants, oil and water transmission systems, etc. However, a review of the subject would not be complete without a brief reference to at least some of the less common situations in which transient pressure waves have arisen, and of other methods of analysis (see refs. (17, 18) for more details).

Digital computers have proved most popular for the development of numerical solutions of general surge problems. Analogue computers have not been ignored (59), but the relative cheapness and ease of access to the digital machines will probably ensure that they will continue to be preferred.

The structural response of fluid conveying systems to transient pressure waves has been observed and analysed by several research workers. From studies of fairly conventional pipe flow situations it has been shown that although the usual one-dimensional analyses normally provide answers that are substantially correct, occasions have arisen when this is not so. These situations include close-return mitred bends having included angles of 90° or less, pipes supported in such a way that significant axial and/or lateral movement can occur, step changes of pressure in thin-walled elastic pipes and pulsatile disturbances in laminar flows, particularly in viscous fluids.

One special situation that has received attention in recent years is the field of safety analyses in nuclear engineering practice. As a result of the large pressure changes associated with molten fuel-coolant interactions the deformation of the flow passages can be quite large, even to the point of plastic deformation and possibly rupture of the duct walls. Various methods have been devised for modelling the situation (60, 61), ranging from two-dimensional finite-element schemes to the simpler one-dimensional models. In terms of the limited experimental data available both types of model appear to give reasonable answers.

Among the other flow situations which have attracted interest in the present context are natural gas transmission lines (62, 63), non-Newtonian fluids such as blood and other body fluids (64, 65), hydraulic mining (66, 67), hydraulic control circuits (missile positioning, die-casting processes) and engine fuel supplies.

The variety of these flow situations underlines the point that any system in which a fluid is in motion, or capable of being set in motion, is susceptible to pressure surge phenomena.

The pursuit of a better understanding of surge phenomena leads almost inevitably to more complex equations and more sophisticated solutions, a situation which is in marked contrast to the needs of the average practising engineer who prefers design charts, and simple, although approximate, laws and equations.

Amongst what are perhaps the more useful examples for pumping lines are equations for estimating the magnitude of the pressure rise following the collapse of the cavity that can form following failure of motive power to the pumps (68), and design charts (69-71) for estimating the size of air vessels to protect such lines from surge effects. A simple equation for a first approximation of air vessel size to avoid column separation in a rising main, which reaches the elevation of the downstream reservoir about three-quarters of the pipe length downstream of the pumps, is Lupton's Law (72), which is

$$\forall = \frac{(H_s + 36.6)\, L.A.V_o}{8361} \quad m^3 \qquad (3)$$

Other approximate methods have been developed for the estimation of pressure rises following valve closures (73), pump starts (71, 74), sizing of air admission and release valves (75).

7 CONCLUDING REMARKS

The general nature of the phenomenon of pressure surge, as it occurs in liquid-filled pipes and conduits, has been well understood for many years. The present position is that the governing equations can be solved by computer-aided numerical methods to yield satisfactory predictions for most practical engineering systems. Nevertheless, there are many features which influence the propagation of transient pressure waves in such systems and which have been, still are, or ought to be, the subject of further research. Examples of these include:

a) non-linear effects such as friction losses in both conduits and fittings and the thermodynamic behaviour of air chambers,

b) transient effects in multi-phase single- and multi-component flows,

c) the behaviour of hydraulic machinery (especially pumps) and valves under time varying conditions,

d) the propagation of large amplitude pressure waves,

e) resonance effects and instability in hydro-power and hydraulic control systems, with particular reference to the behaviour of boundary conditions.

In conclusion it is hoped that this review will serve as an initial source of references and a resume of present knowledge of transient phenomena in pipes and pipe networks for both practising engineers as well as research workers, and provide some thoughts on possible lines of future research activity.

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