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Transient friction in pressurized pipes; the water hammer phenomenon

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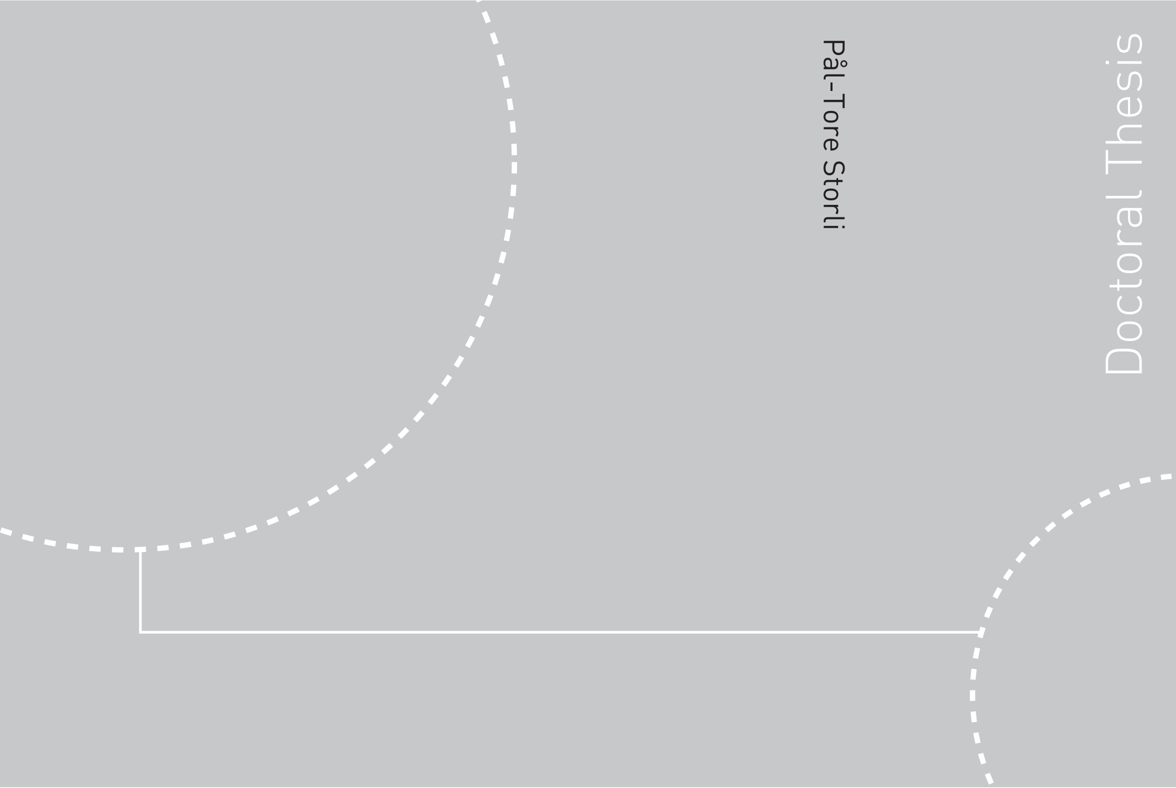

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Thesis for the degree of
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Department of Energy and Process Engineering

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Thesis for the degree of philosophiae doctor

Trondheim, June 2010

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To my family and to all my loved ones: Thank you for your support

To my mother: I hope you would have been proud

To Hilde: I was a sailor; I was lost at sea,
I was under the waves before love rescued me,
you’re my love

Abstract

The friction in non-stationary flow is an intriguing and interesting phenomenon. Many types of non-stationary flow exist, and the friction involved in these flows is in many cases significantly different from the steady state friction for the same instantaneous flow. Knowledge of this friction is important for many different fields of engineering, such as dimensioning of pipeline systems, operation and maintenance of pipeline systems, water quality monitoring and stability of the operation of governed components in pipeline systems.

Unsteady fluid flow where friction is included is not easily computable, at least not if detailed transient information is desirable for long duration simulations. The complexity in phenomena involved in transients in fluid flows is huge, and simplifications justified for some transient flows might very well be highly erroneous for others types of flows. A general and comprehensive model for the friction involved in transient flow is highly desirable, but unfortunately the models that are closest to meeting this desire is not practically applicable due to the computational demands of the models. One-dimensional models are simple and applicable from a practical point of view, but their accuracy has traditionally been limited. One-dimensional models have been able to simulate maximum peak pressures for single pipelines, but not the general dynamics of the pressure-time history with correct dampening. This is a problem in pipeline systems because dimensioning pressures are not necessarily only dependent on peak pressure values but also the decay and build-up of the pressure-time history.

The work presented in this thesis is using a novel methodology in order to find coefficients that highly improve the accuracy of one particular one-dimensional unsteady friction model for the case of a sudden closure of a downstream valve for an initial flow at low Reynolds number. The methodology in finding these coefficients is based on the unique periodicity of local accelerations that occur due to the pressure wave that travels between boundaries and the physically founded weighting function used in the Convolution Based models. This cause the two coefficients used to become position dependent, thus curving the characteristic lines in the Method of Characteristics solution scheme. The improvement is not proven general, but the methodology represents an improvement of simulated pressure traces that is significant. The approach in finding these coefficients is based on physical considerations, although the methodology itself must be classified as empirical.

Preface

The work which this thesis is the result of has been performed at the Waterpower Laboratory at NTNU in Trondheim, Norway, in the period from August 2007 to June 2010.

I would like to express my gratitude to my colleagues at the Waterpower laboratory for the nice work environment here and the valuable transfer of knowledge that is taking place in the fruitful discussions we have. Further I would like to thank Dr. Anton Bergant for lending us experimental results, and permitting us to use them in publications. The experimental results have been paramount in order to be able to test different models and also with respect to finishing this thesis on time. My supervisor and co-author on papers Torbjørn K. Nielsen deserves to have a statue of him casted in bronze for always being available for questions and discussions. Consultant Wenche Johansen's guidance in the maze of regulations is also highly appreciated, along with the motivational manner of co-supervisor Ole G. Dahlhaug. I would also like to thank the administrative staff at the Department of Process Engineering, especially Anita Yttersian and Gunhild Valsø Engdal for their help regarding things of administrative nature during the working period, as well as Eugen Uthaug for all the help I have received regarding computer problems during this period. Kjell Tore Fjærvold at Statkraft also deserves to be mentioned and thanked because of his motivational enthusiasm for the work performed at the Waterpower Laboratory.

The work has sometimes seemed unmanageable, boring and governed by formatting of papers and manuscripts which is not a very stimulating type of work. Fortunately, the work has for most of the time been interesting, rewarding and has been dominated by a child-like enthusiasm over the findings and progressions made.

Sometimes the race for new knowledge occurs on a crowded highway. Clamped between moving vehicles it can be difficult to find exits, and it can be even more difficult to manoeuvre yourself so that exits can be used. Initially being a novice in the field of science that this thesis is considering, I found myself at the very edge of the highway, and therefore I found an easy exit not far ahead. As the poet Robert Frost wrote; "two roads diverged in a wood, and I-- I took the one less travelled by, and that has made all the difference".

Hopefully, the road less travelled by will not turn out to be a dead end, and if so I will be sure to place a sign at the exit telling everyone else this.

Pål-Tore Storli, Trondheim, June 12th 2010

Acknowledgments

This work has been a part of the project SyDK-5 funded by Energi Norge, a trade organisation for about 260 generators, suppliers, distributors and contractors in Norway. Their generally positive attitude towards supporting the work at the Waterpower laboratory at NTNU is highly appreciated. The experimental results that so kindly were lent us were obtained from tests at the University of Adelaide, Australia, and the work leading up to those results was supported by two large grants from the Australian Research Council. The experimental results have been paramount for the work leading up this thesis, and for this reason are gratefully acknowledged.

Structure of thesis

This thesis is comprised of a summary; Part I, and the following papers found in Part II:

Paper A: TRANSIENT FRICTION IN PRESSURIZED PIPES; INVESTIGATION OF ZIELKE'S MODEL

Parts of the work found in this paper was presented at the IAHR 24th Symposium on hydraulic machinery and systems in Foz Do Iguazzu, Brazil, 2008 (Storli and Nielsen, 2008)

The paper has been submitted to Journal of Hydraulic Engineering (JHE); a journal published by American Society of Civil Engineering (ASCE), and has been accepted for publication.

Paper B: TRANSIENT FRICTION IN PRESSURIZED PIPES; A TWO-COEFFICIENT INSTANTANEOUS ACCELERATION BASED MODEL

Parts of the work found in this paper was presented at the 3rd IAHR International Meeting of the Workgroup on Cavitation and Dynamic Problems in Hydraulic Machinery and Systems in Brno, Czech Republic, 2009 (Storli and Nielsen, 2009), as well as presented at a meeting for the project Hydralab III at Deltares, Delft, The Netherlands, May 2009.

The Paper has been submitted for publication in JHE, ASCE, and is currently in the second round of reviewing.

Paper C: TRANSIENT FRICTION IN PRESSURIZED PIPES; INVESTIGATION OF THE EIT MODEL BASED ON CURVED COEFFICIENT APPROACH IN MIAB MODEL

The paper has been submitted for publication in JHE, ASCE, and is currently in the first reviewing round. If accepted, it is likely to be as a technical note.

Contents

Part I: Summary

Part II: Papers

Part I

Summary

1 INTRODUCTION

> ” An ocean traveller has even more vividly the
> impression that the ocean is made of waves
> than that it is made of water”
> -Arthur S. Eddington

The universe is the playground for transients. Thus, understanding the universe means understanding transient phenomena. The purpose of the PhD-work which this thesis is the result of, is to find simple but more accurate models of unsteady friction based on understanding of the friction in transient flow in pressurized pipes. The term “understand” is a qualitative one; yet the measure of an understanding within the field of engineering sciences is usually quantitative. This poses a contradiction; a quantitatively correct measure does not necessarily imply a qualitatively correct understanding. Hopefully, this is not the case for the work presented in this thesis.

1.1 Objective of the work

The objective of the work has been to try to find a simple but accurate representation of the frictional losses in transient flow in pressurized pipes. Accurate models exist, but they are so computationally demanding that they are not applicable from a practical point of view. These models are typically models in more than one dimension using some turbulence model. The motivation for trying to find a simple and accurate model for the frictional transient losses was originally from a hydropower point of view. The changes in operational loads for hydropower plants induces transients in the water way system, and the friction in this transient flow will affect operational cost as well as stability criteria for operation of the plant. Better knowledge about these two properties is desirable for power companies.

At the beginning of the work presented in this thesis, an extensive literature search was made. It felt necessary to start with the first major contributions to this field of research and chronologically read contributions up to present time. The amount of work that had been made in this field of research was much higher than anticipated, and the intensity of effort amongst the research community had increased the last two decades. Since the work of others was, at least mainly, read in a chronological way, many of the questions and approaches for improvement that arose reading one particular paper had been answered and tested by others later on.

When the work presented in this thesis was in the starting phase, one would assume that a hypothesis was made. However, this was quite difficult to do since the literature search revealed that so much work had been made in this field of research, no apparent white areas on the map seemed to exist. Because of this, the work got a sort of “let’s see if we can find something interesting”- approach to it and a hypothesis for the project as a whole became quite difficult to establish. If at all something remotely close to a hypothesis was made, it was only established mentally and would serve as a purely motivational mantra in order to keep spirits up. This mantra, if written down, would have been something like “it is possible to improve unsteady friction modelling based on physical considerations”.

Since no clear and scientifically proper hypothesis governed the project, the decision of which path to take was decided as time and work progressed. However, at each junction hypothesis-like questions would appear, biasing the decision in which to go in one direction. This approach is quite typical for basic research, and the work presented in this thesis is somewhat a quasi-basic research in the sense that the path of the investigations has been driven by curiosity. However, the main desire has been applicable knowledge, which (hopefully) has been obtained in the end.

A comprehensive model for transient friction for operational changes on hydropower plants has not been obtained in the work presented in this thesis. However, a correctional model for low Reynolds number flow subjected to a sudden closure of a downstream valve in a single pipeline has been found, for the time being not proven general. This improvement can hopefully, in the future, turn out to be the basis for an improved model for pipeline systems, including hydropower systems.

1.2 Introduction to the water hammer transient

Unsteady fluid flow in pipes can be divided into two main categories; uniform flow and non-uniform flow (Wylie et al., 1993). Uniform flow is the case where the average velocity in each cross section of a pipe is identical. This is typically slow transients where the fluid is acting as a rigid column like in a u-tube oscillation. Non-uniform flow is the case where the average velocity in each cross section of a pipe is not identical. This is typically rapid transients where the changes at one point significantly change the flow and pressure before this information has reached all other cross sections, for instance a sudden closure of a valve in a pipeline. This latter case makes properties of the fluid and pipe paramount and the changes in flow and pressure are propagating through the pipeline or pipeline system with the effective speed of sound for the fluid and pipe as two interacting entities. The work presented in this thesis is only considering the non-uniform flow transient.

The water hammer transient is a non-uniform flow which is a change in the pressure resulting from a sudden change in the flow. This wave of altered pressure is propagating with the speed of sound through the pipe, and accompanying this pressure wave is the change of the flow which was the cause of the pressure change in the first place. At boundaries the pressure can be reflected and propagate back to the origin of the pressure change, and the flow behaves thereafter. This pressure- and flow variation continues to travel between boundaries, and the friction present in this flow is damping the value of these variations, finally giving a new steady state value for the flow under consideration.

For the case of a full closing of a valve (in the figures considered a linear deceleration of the flow to zero), the friction free transient can be illustrated by the following animation:

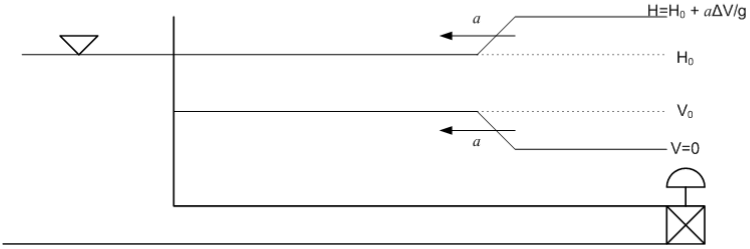

Figure 1-1: Pressure and flow, 0<t<L/*a*

Initially, we have the values for the flow and the head denoted by the properties with subscripts zero. A linear deceleration of the flow by the operation of the valve initiates a linear pressure rise. The changes in pressure and flow propagate with the speed of sound towards the upstream reservoir. When the changes reach the upstream reservoir there is an unbalanced condition because the pressure at the reservoir is constant. At this moment the entire pipe is containing high pressure water with no velocity. The unbalanced condition forces the flow in the opposite direction, while the pressure drop to the initial value

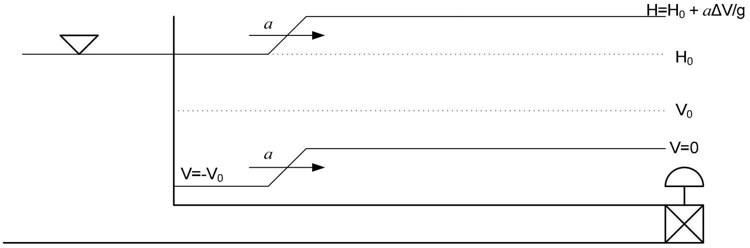

Figure 1-2: Pressure and flow, L/*a*<t<2L/*a*

This wave is propagating towards the closed valve, and after the wave has passed any cross section in the pipe the pressure is at initial value, but the flow is now in the direction towards the upper reservoir. The valve is closed, so when this flow reaches the valve is has to be stopped. This creates a pressure drop, and this pressure drop is propagating towards the reservoir while the flow is returned to zero value.

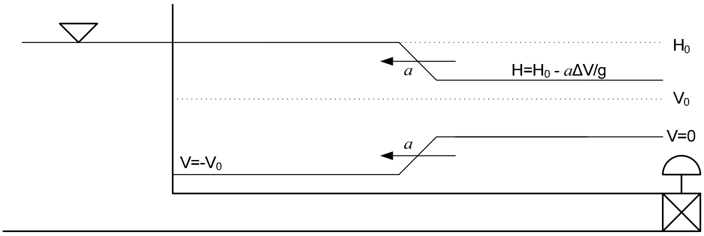

Figure 1-3: Pressure and flow, 2L/*a*<t<3L/*a*

However, at the reservoir the unbalanced condition is still present, but this time with opposite sign. This causes a wave to propagate towards the valve, creating once again the initial condition in the pipe.

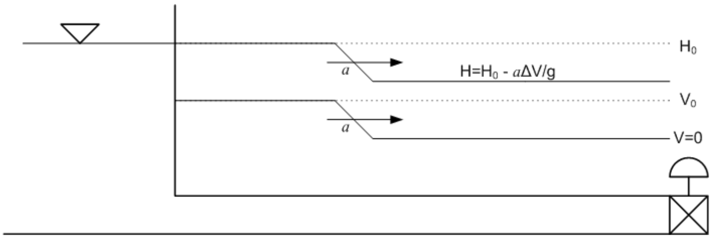

Figure 1-4: Pressure and flow, 3L/*a*<t<4L/*a*

The valve is still closed, so when the wave reaches the valve, the cycle repeats again starting from Figure 1-1. Damping will change the magnitude and shape of the pressure and flow trace as this transient progress in time, and this damping is not easily found. This thesis is an investigation of this damping.

1.3 The History of the Water Hammer and Unsteady Friction

Much of the information in this chapter is found in the comprehensive paper by Ghidaoui et al., (2005), which is an excellent review of this field of research.

Probably, the best known pioneers (but certainly not the first) in the field of investigation of the water hammer phenomenon are Joukowsky and Allievi. The water hammer phenomenon is the pressure rise in pipes where the flow is rapidly stopped. This pressure rise is a potentially destructive one, and an accident due to this pressure rise in Papigno power plant in 1902 in Terni, Italy, initiated an investigation by Allievi which resulted in his fundamental study of the water hammer problem. Along with the effort of, amongst many, Streeter and Wylie, the classical one-dimensional (1D) governing equations for water hammer transients were established in the 1960s. They have later been analyzed in several works, and still stand as the fundamental equations for the water hammer transient (Ghidaoui et al., 2005).

The friction involved in the water hammer phenomenon has been intensively investigated for many years. The total friction involved in the water hammer transient phenomenon is typically divided into two terms. The first term is the term that is commonly referred to as “quasi-steady friction". It computes the friction according to steady state formulas, but uses the instantaneous and time-dependent flow to calculate the numerical value, thus being a quasi-steady assumption. The second term is the purely unsteady friction term, which is acting as a correction of the quasi-steady assumption. This division of the friction into a quasi-steady and an unsteady part is convenient because the presence of the quasi-steady term ensures that friction will be correct for any new steady state flow. For the calculation of the unsteady friction term, many different models and approaches have been presented, seen as classified into six groups in Bergant et al., (2001). Some are very complex in nature and utilizes turbulence models and multi-dimensional approaches in order to find the wall shear stress, whereas some models are simple and based on empirical coefficients and instantaneous accelerations. The different models have been divided into two fundamentally different classes; one that represents empirical based models, and one class that represents physically based models (Ghidaoui et al., 2005).

1.3.1 Empirically based models

One of the first empirical models for calculation of the unsteady friction term was the model by Daily et al., (1956). It uses the local acceleration of the mean flow to calculate a term that is used as the unsteady term correcting the quasi-steady assumption. This model was found equivalent to the wall shear stress which could be obtained from a velocity profile that obeyed a power law (Carstens and Roller (1959), cited in Ghidaoui et al., (2005)). This power law did not allow for flow reversals in the velocity profile, a phenomenon that is present in the water hammer phenomenon. Brunone et al., (1991) modified the Daily model to incorporate the spatial derivative of mean flow using the Coriolis correction coefficient. This improved simulation significantly compared to experimental results, and has become the most widely used model in water hammer applications due to its simplicity (Ghidaoui et al., 2005). The Brunone model was further modified by Pezzinga, (2000) and Bergant et al., (2001) to generalize the model for arbitrary valve position by giving the correct sign of the spatial derivative term for closing of an upstream or downstream valve, as well as providing the correct sign for the unsteady loss at different periods of the transient (Vitkovsky et al., 2006a).

The Brunone model uses a coefficient k_3 to "tune" the magnitude of the unsteady friction term. This term has proven, unfortunately, not to be a constant. Many different values for the coefficient can be found in the literature. Pezzinga (2000) found diagrams much like the Moody-chart for the prediction of the coefficient using a quasi-two-dimensional (two-dimensional, 2D) turbulence model. Continuous computation of the coefficient using the latest consecutive pressure peaks were performed by Brunone et al. (1995) and Bouazza and Brunelle (2004). Vardy and Brown (2003) found a coefficient based on theoretical approaches as an equation utilizing a decay coefficient determined by physical properties. This latter coefficient has been used both based on initial values and based on dynamical properties during the transient (Vitkovsky et al., 2000). Loureiro and Ramos (2003) divided the single coefficient into two different coefficients, one for each of the derivative terms, in order to better match results from experiments with plastic pipes.

Axworthy et al. (2000) developed a model based on extended irreversible thermodynamic, which partly supported the models using local acceleration and spatial derivative of the flow to determine the unsteady contribution to friction. Their model uses local and convective accelerations, but it suffers from the draw-back of having to use a coefficient not analytically obtainable in order to get the correct amount of unsteady friction.

Recently, a novel model was presented by Pothof (2008), which models the unsteady contribution to friction by combination of two new approaches called *history velocity* and *transient vena contracta*. The simulation results show good agreement with experimental results for several different transients performed on different pipeline configurations. Pothof uses some of the same experimental results as have been at hand for the work in this thesis, from tests performed at University of Adelaide. However, there is a discrepancy between the stated wave speed for his simulations and the wave speeds stated in his reference Bergant et al. (2001) for this test (1283 m/s vs. 1319 m/s). The match with experimental results might not be so good if it turns out that the wave speed has been assumed different in simulations to what they actually were in the experimental tests. However, the approach is interesting, and several researchers commented on the findings (Duan et al., 2009).

1.3.2 Physically based models

The physically based models are not in need of calibrated coefficients. They are *a priori* models which are based on physical consideration. A large class of the physically based models are developed from the pioneering work and approach by Zielke (1968). This model was originally developed for laminar initial flow and gave a physical translation of 2D effects for the use in 1D analysis. Analytical work using the Navier-Stokes equation in radial direction allowed Zielke to link wall shear stress (as defined by the velocity gradient at the wall multiplied with the viscosity) to the mean local acceleration of the flow via a weighting function utilized in a convolution integral with the history of local accelerations of the mean flow. The convolution procedure acts as a memory of the effect of past accelerations, and the decaying weighting function is carrying the information of the amount of reduction of radial velocities within the velocity profile. This approach is computationally demanding since the convolution procedure needs to weight the ever increasing time-history of mean velocities. Several researchers have presented work that tries to increase the speed and reduce the storage demand of the convolution procedure. Trikha (1975) approximated the weighting function found by Zielke as three exponential terms, allowing for a much more rapid recursive procedure. Suzuki et al. (1991) maintained the accuracy of the Zielke model while reducing the computational effort by using a partial convolution and a recursive formulation, a sort of hybrid between the original Zielke model and Trikha approximate model. Vardy and Brown (2003) extended the convolution method into the turbulent regime for hydraulically smooth pipe flow by generating weighting functions for turbulent initial flows by assuming a frozen viscosity distribution. Later, they extended the method to be valid for fully rough turbulent pipe flows (Vardy and Brown, 2004). Ghidaoui (2002) made an efficient recursive formulation of the Vardy-Brown weighting functions so that computations could be performed at much higher speeds. Vitkovsky et al. (2004) also reduced computational effort for both the laminar and turbulent regime by approximation on the Zielke and Vardy-Brown weighting functions, respectively.

Other models have been developed that are also based on physical considerations of the flow. Quasi 2D models have been developed (Pezzinga, 2000, Pezzinga, 1999), which computes the velocity profile between computational nodes used in a 1D simulation. The obtained velocity profile then allows for the computation of the wall shear stress which is implemented as a numerical value in next computational step in the 1D simulation. If the simulation is in the laminar regime and the laminar assumption hold for all transient periods this will give the same results as using the original Zielke full convolution model. However, since the velocity profile is computed continuously, the information contained in the original Zielke convolution procedure is lumped into the velocity profile at previous computational time step. This avoids the almost exponential increase in computational time seen in full convolution procedures, but the determination of the velocity profile in between all computational nodes is also computationally expensive. For quasi 2D models in the turbulent regime, the use of a turbulence model is needed. Researchers have used many different models and also divided the flow into different concentric layers in the cross section, allowing for a more accurate description of the turbulent phenomena at different radii of the pipe. The advantage of the quasi 2D models in the transient regime, compared to weighting function models, is that the quasi 2D models are not limited to the frozen viscosity assumption that is used in the development of the appropriate weighting function for the turbulent flow. However, this advantage has proven not to give a great improvement in simulation results, as the effect of the, with time, increasing erroneous frozen viscosity assumption has less and less effect on the simulations (Vardy and Brown, 2003).

1.4 The importance of transient friction

When it comes to simulations of hydraulic transients, transient friction is not always important. There are transient cases where acceptable results are obtained by friction free simulations, but these cases are usually for simulations of very small durations after the transient is initiated, so small that simple considerations are sufficient and simulations are not strictly needed. If the objective is simulation of transient times well beyond the first cycle the modelling of transient friction is paramount for ensuring high quality results. Examples of cases where transient friction should be incorporated include (Ghidaoui et al., 2005):

- The design and analysis of pipeline systems
- The design and analysis of transient control devices
- The modelling of transient-induced water quality problems
- The design of safe and reliable field data programs for diagnostic and parameter identification purposes
- The application of transient models to invert field data for calibration and leak detection
- The modelling of water column separation and vaporous cavitations
- Systems where the time for pressure wave propagation in one pipe length is much smaller than the time scale for radial diffusion of vorticity

A parameter $\Gamma=\zeta LMf/2D + \zeta T_d/(L/a)$ has been defined to evaluate cases where transient friction is important (Ghidaoui et al., 2005). ζ is the length of simulation time, L is the pipe length, M is the mach number, f is the Darcy-Weisbach friction factor, D is pipe diameter, T_d is radial diffusion time scale and a is the wave speed. The friction is important when the parameter Γ is bigger than 1. The first term in the parameter can be attributed to quasi steady behaviour of the flow. Quasi steady behaviour is the assumption that the velocity profile has the shape according to steady state flow corresponding to each instantaneous flow value during the transient. This is rarely a valid assumption, and the latter term can be attributed to unsteady behaviour, i.e. the deviation of the real behaviour from quasi steady behaviour. The parameter T_d is decreasing with increasing Reynolds number, so generally one can say that for increasing Reynolds number and increasing pipe length, the contribution of unsteady friction to the total friction become less important. However, if the simulation time is long the term might be important even if Reynolds number is high and the pipeline is long.

2 GOVERNING EQUATIONS AND MODELS OF 1D TRANSIENT FRICTION

2.1 Governing equations

The governing equations describing transients in flows are derived from considerations regarding momentum and continuity for a fluid element in a pipe. The derivation of these equations is found throughout the literature, and they constitute the 1D wave equation or different forms of this. For low compressible fluids and flow velocities much lower than the Mach number unity, simplifications to the general equations are justified, causing the convective acceleration term to be negligible in both the momentum and continuity equations. The resulting equations become (Wylie et al., 1993)

$$\frac{\partial \boldsymbol{H}}{\partial \boldsymbol{x}}+\frac{1}{\boldsymbol{g}}\frac{\partial \boldsymbol{V}}{\partial \boldsymbol{t}}+\boldsymbol{h}_f=0 \tag{1}$$

$$\frac{\partial \boldsymbol{H}}{\partial \boldsymbol{t}}+\frac{\boldsymbol{a}^2}{\boldsymbol{g}}\frac{\partial \boldsymbol{V}}{\partial \boldsymbol{x}}=0 \tag{2}$$

H is the piezometric head, x is the space variable, g is the gravitational constant, V is the bulk flow velocity, t is the time variable, h_f is the head loss per unit length. The limitations to these equations are that they are valid for slightly compressible fluid flow at low velocities in pipes with uniform cross section area.

The head loss is commonly divided into a quasi-steady term and an unsteady term. This division is quite convenient because a new and correct steady state flow will be obtainable as a limit when the unsteady effects have vanished from the transient, which by definition *are* steady state conditions. This friction formulation is as seen in Eq. 3, for the time being the unsteady term is left undefined.

$$h_f = h_{f,q} + h_{f,u} = f\frac{V|V|}{2gD} + h_{f,u} \tag{3}$$

$h_{f,q}$ is the quasi-steady head loss per unit length, $h_{f,u}$ is the unsteady head loss per unit length.

The quasi-steady term is computing the head loss determined from the steady-state friction coefficient, but the coefficient is (usually) updated for the Reynolds number corresponding to the instantaneous flow velocity. The sign of the quasi-steady head loss per unit length is also maintained in this formulation, using the velocity squared will not give the correct sign when combined in the governing equations. This quasi-steady representation is basically stating that the head loss at any instant is the same as the steady-state head loss corresponding to a stationary bulk velocity equal to the instantaneous bulk velocity. This term is implying a velocity profile and velocity gradient at the wall equal to the fully developed velocity profile corresponding to the instantaneous flow velocity. However, this is not true in transients with rapid and large velocity gradients. The velocity profile near the wall undergoes dramatic changes if the gradients are large, with possible flow reversal at the wall, the so-called annulus effect (Abreu and de Almeida, 2009, Pezzinga, 1999, Brunone et al., 1995, Vardy and Hwang, 1991). The unsteady term in the head loss representation is intended to include effects of the deviation between actual transient behaviour and the quasi-steady assumption. It is this term that is difficult to find in an easy and sufficiently correct way, and different models representing these terms are described in the following.

2.2 1D models of unsteady friction

1D models are the fastest models of computing hydraulic transients, simply because the representation of the problem is at its simplest and most reduced form. No computations are performed in radial or tangential directions, all computations are “lumped” into strictly axial considerations. Properties and parameters might very well have been found based on considerations of radial and tangential effects, but no real computations of dynamic behaviour in these directions are performed in a 1D model. 1D models can also be coupled with computations in radial and/or tangential direction, possibly the easiest example being the so called quasi 2D models where the velocity profile is calculated in parallel to the 1D simulation based on information from the 1D simulation results, and the velocity profile is then utilized to find parameters for use in the next computational step in the 1D simulation. In this way a more precise simulation is obtained, but at the expense of computational time and effort. In general, the more complex models and simulations are, the better results are obtained. However, in engineering practices the 1D models are dominating because of their simplicity.

The 1D models that are applicable in engineering practices can be divided into three basic categories; based on past history the of bulk accelerations; based on instantaneous accelerations and based on irreversible thermodynamics (Vardy and Brown, 2003). These categories are presented in the following.

2.2.1 Convolution Based (CB)

The models that are based on the past history of bulk accelerations are also referred to as Convolution Based (CB) models since the accelerations are utilized in a convolution integral. Originally developed by Zielke (1968) for laminar flow, it has been simplified and refined for more rapid computations by, among others, Trikha (1975), Kagawa et al. (1983) (cited in Vitkovsky et al., 2006b, Suzuki et al., 1991, and Schohl, 1993). The original model of Zielke is mathematically defined as

$$\boldsymbol{h}_{f,u} = \frac{16\upsilon}{\boldsymbol{g}\boldsymbol{D}^2}\int_0^t \frac{\partial \boldsymbol{V}}{\partial \boldsymbol{t}}(\boldsymbol{u})\boldsymbol{W}(\boldsymbol{t}-\boldsymbol{u})\boldsymbol{d}\boldsymbol{u} \tag{4}$$

υ is the kinematic viscosity, *u* is the convolution time and *W* is the weighting function.

The typical simplifications to this method has been of the type where the original weighting function *W* has been approximated by the sum of various number of exponential functions, allowing for a much easier recursive formulation of the computationally demanding convolution integral.

The CB method has been further developed to be valid for smooth pipe flow in the turbulent regime by several researchers. They developed weighting functions for the turbulent regime by dividing the flow into separate layers with different turbulent viscosity distributions. Zarzycki (2000) made a four-layer model, the resulting analysis being too complex for use in general solutions but providing valuable confirmation of the acceptability of the two-layer approach by Vardy and Brown (2003) (cited in Vardy and Brown, 2004), which was a further refinement to the first model by Vardy et al. (1993). Vardy and Brown (2004) further extended the methodology to be valid for fully rough flows by determining new weighting functions dependent not only by the Reynolds number but also on the roughness size. The Vardy-Brown and Zielke weighting functions have been simplified for more rapid computations by Vitkovsky et al. (2004), and the Vardy-Brown weighting functions have been simplified by Ghidaoui (2002).

One of the great advantages of CB models is that they are based on physical considerations and not dependent on coefficients that has to be found or determined in some way, making them generally applicable for fluid transients, although not with the same accuracy for continuously accelerating or decelerating flows as for the rapid valve closing water hammer transient (Vitkovsky et al., 2006b).

An investigation of the CB model using the original Zielke weighting functions was performed in the beginning of the work that is presented in this thesis. This investigation led to the submission of a manuscript for a paper, submitted to JHE (ASCE) and accepted for publication. A summary of this paper is found in sub clause 4.1, the paper itself is found as Paper A in Part II: Papers.

2.2.2 Instantaneous Acceleration Based (IAB)

The IAB models are rapid and easy to implement in numerical schemes. The basic model of Daily et al. from the mid-fifties has been modified and refined by Golia, Brunone, Pezzinga and Bergant et al. (Cited in Vitkovsky et al., 2006a, Bergant et al., 2001). The IAB models are dependent on one or two coefficients that have to be determined in order to compute the correct amount of unsteady friction. For this reason they are not *a priori* models and finding the correct coefficients often means to have experimental results in order to calibrate the coefficients. The single coefficient have been found in many different ways; empirically found from comparison with experimental results, using analytical relations (Vardy and Brown, 2003), found from previous peak pressures in the transient (Bouazza and Brunelle, 2004, Brunone et al., 1995) and post-calculated from more complex models (Brunone et al., 2003, Pezzinga, 2000). The coefficient has effectively been both time and space dependent in several of these approaches. A different approach has been to use two coefficients; one for each of the derivative terms in the IAB representation of unsteady loss. This approach has showed to potentially give a more general match with experimental results, although now two coefficients need to be determined instead of a single one (Loureiro and Ramos, 2003).

Mathematically the unsteady friction model is defined, in the most general IAB form, as (Vitkovsky et al., 2006a):

$$\boldsymbol{h}_{f,u} = \left(\frac{\boldsymbol{k}_t}{\boldsymbol{g}} \frac{\partial \boldsymbol{V}}{\partial \boldsymbol{t}} + \frac{\boldsymbol{k}_x \boldsymbol{a} \boldsymbol{\phi}}{\boldsymbol{g}} \frac{\partial \boldsymbol{V}}{\partial \boldsymbol{x}} \right) \tag{5}$$

Here, k_t and k_x are coefficients to be determined.

The coefficient Φ is defined as

$$\phi = 1 \qquad \text{for} \qquad V\frac{\partial V}{\partial x} \geq 0$$

$$\phi = -1 \qquad \text{for} \qquad V\frac{\partial V}{\partial x} < 0$$

This coefficient was introduced in order to modify the model so it produced the correct sign for the damping regardless of the position of the valve in the system. Different positions of the valve produce different sign for the spatial derivative term, so this modification ensures that the model never produces unrealistic increases in pressure (Vitkovsky et al., 2006a). This modification also ensures that the sign of the unsteady friction term is correct for different periods of the transient (Vitkovsky et al., 2006a). This model (Equation 5) is therefore called the Modified IAB (MIAB). In the single coefficient model the two coefficients k_x and k_t are equal, thus linking the two derivative terms to each other. In the two-coefficient formulation the different coefficients will be responsible for different behaviour, so using this formulation potentially allow for more accurate modelling of transients. Analysis has showed that the temporal derivative term is exclusively involved in the phase shifting phenomenon of the problem, whereas the spatial derivative term is only involved in the damping of the transient (Vitkovsky et al., 2006a).

Unfortunately, the constant coefficient MIAB model does not work well for valve opening transients (Vitkovsky et al., 2006a). This is unfortunate since transients events analogous to valve openings are likely to occur in pipeline systems, even if the initiating transient is a valve closing event. However, the coefficients found applicable and reported for the MIAB model seems mostly to have been found for valve closure events, and the phenomena involved in these events are fundamentally different from valve opening events. The mismatch between MIAB simulations and simulations using more complex models might very well be attributed to unrealistic MIAB coefficients, rather than a general failure of the MIAB model. However, if an improvement of the MIAB model for valve opening transients is to be found, the coefficient most likely cannot be independent of time as a time-invariant coefficient would yield the same form of the differential equations as equations (13) and (14) presented in Vitkovsky et al. (2006a), which is shown gives no additional damping, and only phase shift.

During the work presented here, the MIAB model for valve closure was highly improved using two different position dependent coefficients based on the unique periodicity of the occurrence of local accelerations at specific cross sections in a pipe and the weighting function used in the CB model. This observation led to the submission of a paper to JHE (ASCE), and this paper is currently undergoing a second reviewing round. A summary of this paper is found in sub clause 4.2, the paper itself is found as Paper B in Part II: Papers.

2.2.3 Extended Irreversible Thermodynamics (EIT)

The EIT model is basically non-equilibrium variables included in the classical equilibrium equation known as the second law of thermodynamics. The representation of the unsteady wall shear stress resulting from this analysis ended up as (Axworthy et al., 2000):

$$\tau_{W,u} = \frac{\rho D}{4} T \frac{\partial V}{\partial t} + \frac{\rho D}{4} T \cdot V \frac{\partial V}{\partial x}$$

6

$\tau_{W,u}$ is the unsteady wall shear stress, ρ is the fluid density and T is a thermodynamic coefficient that needs to be determined.

The relation between unsteady head loss per unit length and unsteady wall shear stress is given by

$$h_{f,u} = \frac{4\tau_{W,u}}{\rho g D}$$

7

This model turned out to give a physical solution that partly supported the latest IAB models that used temporal and spatial derivatives to calculate unsteady friction in the sense that the unsteady friction terms in EIT is given by a term proportional to the temporal and convective acceleration (Axworthy et al., 2000, Vardy and Brown, 2004). The coefficient T in the EIT model represents a relaxation time, and needs to be determined from experiments. According to Axworthy et al. (2000) the coefficient needs to be positive. Further, they argue that a positive T implies decreased friction in decelerated flows and increased friction in accelerated flows. The claimed requirement of a positive T is said to be consistent with the limitations of the model to transients governed by short timescales, and that this short timescale requirement is essentially a requirement that radial distributions of velocity in the flow can be neglected.

One of the findings from the EIT analysis by Axworthy et al. (2000) was that the constant coefficient MIAB model is implying that dissipation terms in the EIT loss model is automatically nullified in some periods of the transient (Pezzinga, 2001). This can be the case in water hammer transients, but has no general validity (Ghidaoui et al., 2001).

The MIAB model using the curved coefficients presented in Paper B was approximately “translated” into an EIT model in a paper submitted to JHE (ASCE). A summary of this paper is found in sub clause 4.3, the paper itself is found as Paper C in Part II: Papers.

2.3 Mathematical tools for solutions

Many mathematical tools have been used in order to solve the governing equations for the water hammer transient. The Method Of Characteristics (MOC, a finite difference method), wave plan method, other finite difference methods and finite volume methods have been used. The MOC is by far the most used and is the method that is found in most available commercial software packages. The MOC is accurate, numerically efficient and simple to program, explaining is popularity (Ghidaoui et al., 2005). Stability criteria are firmly established and the method is capable of handling complex systems and has the best accuracy of the finite difference methods (Wylie et al., 1993). The MOC has been used in the work presented in this thesis, and is described in more detail in the following.

2.3.1 The Method Of Characteristics (MOC)

The MOC is the most widely used tool for simulation of fluid transients. The approach used in the MOC is to transform the partial differential equations into finite difference equations valid along lines called characteristic lines in the space-time plane. The method combines the two equations 1 and 2 with an unknown multiplier and uses the concept of the total derivative to solve the unknown multiplier (Wylie et al., 1993). The numerical value of this multiplier is defining the slope of the characteristic lines along which the finite difference equations are valid, and since the multiplier is found as the root of a term, it will always have a positive and negative value. Since the slope of the characteristic lines have both negative and positive values they will define a grid made up of lines where the total difference equations are valid. In the nodes of this grid the solution can be obtained by using previously calculated properties from each characteristic line. As a consequence of this information travelling along the characteristic lines, boundary conditions at all times must be known in order to find solutions at all times. If only initial conditions are known, the solution can only be obtained within the domain defined by the characteristic line from the left initial boundary, right initial boundary and initial time in the space-time plane. Solutions would then be obtainable within a pyramid-like region in the space-time plane. In order to obtain solutions for a practical duration for the water hammer transient the boundary conditions are usually set to zero flow at the closed valve and a constant pressure at the upper reservoir. This allows for simulation of long duration transients.

The grid used in the numerical solution can be defined by the user and is subject to tradeoffs between simulation accuracy and computation expenses and simulation time. However, it is convenient to establish the grid so that the characteristic lines from the initial timeline nodal points also go through the nodal points in the rest of the grid. If the characteristic lines become defined as Eq. 8 this is easily obtained using a rectilinear or diamond grid.

$$\frac{\Delta x}{\Delta t} = \pm a \tag{8}$$

Δ[ ] is the incremental value of the bracketed property.

If the slope of the characteristic lines is not constant in space and/or time, interpolation of previously calculated properties from the simulation must be performed in order to find grid nodal point values. If the grid is coarsely meshed, these interpolations will be subject to possible large interpolation errors. For the work presented in this thesis, the interpolation used is space-line interpolation or reach-out-in-space interpolation (Ghidaoui and Karney, 1994) according to what is necessary.

(Ghidaoui and Karney, 1994) showed that a reach-out-in-space interpolation is a weighted solution to the superposition of two water hammer problems, each of which having wave speeds different from that of the physical water hammer under consideration. The space-line interpolation is essentially introducing a diffusive term, and both interpolation methods fundamentally alter the physical problem. They further state that the only way of achieving accurate, general solutions for hyperbolic problems is to keep the time step small and Courant number as close to unity as possible.

Keeping the Courant number as close to unity as possible is in essence to say that the characteristic lines should cross the time-lines as close to a computational node as possible. The closer to the node the characteristic lines cross a time-line, the smaller the numerical error in the interpolation becomes. Hence, our desires in order to minimize overall numerical error is to have a small time-step, and many computational nodes in the pipe.

For the stability of the solution it is required that the Courant number is not higher than one, since values higher than one will not give a convergence of the numerical solution with the solution of the partial differential equations if the grid size increments go towards zero, i.e. the number of computational nodes goes to infinity (Courant-Friedrichs-Lewy (CFL) condition) (Courant et al., 1967). What the CFL condition essentially is requiring is that there is no extrapolation of values; all values used in the numerical scheme must be found by interpolation between already computed solutions at previous time-steps, the characteristic lines must cross the previous time-line in-between nodes where the values are known. If the space-line and reach-out-in-space interpolations are correctly performed the stability criteria is always fulfilled.

If the time- and space-increments of the numerical grid is linked as described by Eq. 8, the desire of having a small time-step and many computational nodes are also linked. In the numerical solution used for the work presented in this thesis, the rectilinear fixed grid used is the nodes defined by the crossing characteristic lines for the constant wave speed problem defined by Eq. 8.

The rectilinear grid in the MOC is subject to the so-called "grid separation error" (Vitkovsky et al., 2000, Vitkovsky et al., 2006b). This error is originating from the fact that the rectilinear grid is made up of two interlaced diamond grids, where each of the diamond grids experience slightly different boundary conditions when steep changes occur at the boundaries. This will typically be the case for a rapid closure of a valve which is the initiator of the water hammer transient itself. However, this error can be seen as a high frequency oscillation in the simulation results, and the implementation of unsteady friction formulation dampens this high frequency oscillation and it will not persist for a long time in the simulations. Typically it is removed after simulation of a few periods of the pressure cycle (Vitkovsky et al., 2006b). However, the overall damping becomes a bit higher when the rectilinear grid is used compared to the diamond grid, probably because the friction model is biasing the pressure towards the low amplitudes of the oscillatory pressure present in the simulation arising from grid separation error. If a finer computational grid is used the amplitudes of the oscillatory pressure is reduced and for this reason also removed more rapidly from the simulations, but the effect of the additional damping due to the oscillatory pressures persists, even when the oscillating pressure is removed from simulations (Vitkovsky et al., 2000). However, this difference in damping also seems to be smaller when using a finer grid, merely visually seen from the presented figures in (Vitkovsky et al., 2000), and not commented by these authors. Still, the magnitude of the grid separation error is small, and is not regarded as a possible cause of false conclusions regarding the findings presented in this thesis.

3 STATUS AND CURRENT RESEARCH

The friction involved in the water hammer phenomenon has been intensively investigated for many years. Several models have been developed that are not 1D in nature, and many of these models are very accurate and match experiments very well. Unfortunately, the computational time and effort involved in utilizing such models are so high that they are not applicable on their own from a practical point of view (Vardy and Brown, 2003), and despite increased computational power since then they are still not useful in engineering practises.

The last half decade, the work done in the field of unsteady friction seem to be dominated by intensive investigation of the fundamental behaviour of the flow in the region near the wall during the transient, i.e. investigation of the turbulence structures involved in the transient flow (He and Jackson, 2009, He, 2008, Zhao et al. 2007, Vardy, 2007, Zhao, 2006). This is obviously an investigation of the basic mechanisms responsible for the friction present in the transient flow, but the use of new and more accurate turbulence models that may arise from such investigations is not likely to improve the applicability of these models in pipe line systems, unless transformed in one way or another into a 1D model. By now, using existing turbulence models, the number of computations necessary to determine the turbulent characteristics is so high that the speed of the computations are much too low for practical engineering purposes. They are most useful in creating simulations that is meant to be “artificial” experimental results for comparison with models that are computationally fast. Improving the accuracy of models that already are applicable seems to be potentially a much more rewarding approach. These models are the class of 1D models described previously in this thesis, which are the most widely accepted applicable models of unsteady friction at present time.

Recently, there seems to be a renewed interest in the velocity profile involved in transient phenomena and the inertial effects present due to the velocity distribution in non-steady flows (Riasi et al., 2009, Abreu and de Almeida, 2009, Brunone and Berni, 2010). This seem to be a valid renewal of interest, since the most dominant assumption in the governing equations is that inertia is well represented by the bulk velocity, and we know that this assumption is not fundamentally correct since the velocity profile is containing a different amount of kinetic energy that the bulk flow assumption (Brunone et al., 1991).

4 SUMMARY OF SUBMITTED PAPERS

In this chapter, the papers produced and submitted are summarized. An introduction to each paper is made, quite anecdotal in its form and describing the motivation for the work which led to the papers. The findings are also mentioned, but for the full overview of the work the papers should be read. The papers themselves are found in Part II.

The time-line of the work that has been performed during this PhD-project can be found in the chronology of the papers made. Since the path of the work was made up as time went by, the track and approaches of the work is basically identical to the submission sequence of the papers.

When this thesis was submitted, the first paper presented had been accepted for publication in JHE (ASCE). This journal has historically published a lot of work relevant to the subject of simulation of hydraulic transients and unsteady friction modelling.

The second paper was at the time of the submission of this thesis undergoing second round of reviewing for publication in JHE. All reviewers of the originally submitted manuscript were positive about its contribution to the field of research.

The third paper was still under first-time reviewing process for publication in JHE when this thesis was submitted.

4.1 Paper A: INVESTIGATION OF ZIELKE'S MODEL

This paper was the first paper to be made during the PhD work presented in this thesis. The CB model is a famous model developed by Zielke in 1968 and the first approach in the PhD work was to establish a numerical scheme where this model was implemented.

The friction in the water hammer phenomenon has been called "frequency dependent" friction, and the frequency defined by the value $a/(4L)$ has been used as a parameter that would characterize the amount of friction involved in the transient. This felt a bit strange since the pressure wave and therefore the change in flow would occur at cross sections in a periodic manner, and not in a harmonic manner as usually implied by the use of the term "frequency". This paradox initiated an investigation of the CB model where the objective was to see how the CB methodology is accounting for this periodicity rather than a harmonic frequency. To ensure that comparisons between the unsteady frictions at different positions in the pipe calculated by the CB model could be performed it was decided that the post-calculation of the CB unsteady friction based on friction free simulations was the most appropriate. Using this approach the effect of the convolution between the weighting function and periodicity of velocity changes could be highlighted without friction itself obscuring the effect of this periodicity.

The investigation into the CB model showed that the effect of the differences in periodicity of the velocity changes gave rise to a difference in the absolute mean value of the unsteady friction for different positions in the pipe. The unsteady friction was zero at the valve if the effect of the initial closing of the valve was neglected, and it increased in an asymptotic way towards the reservoir. If the pipe length was increased, the mean value of the unsteady friction grew more rapidly towards an asymptotic value, but the asymptotic value was lower than for the shorter pipes. To the authors' knowledge this had never been reported earlier, despite being an intrinsic and undoubtedly important feature of the CB model. The conclusion from the findings was that a position dependency for the unsteady head loss seems to exists, and that this effect included into other and numerically simpler models of 1D friction possibly could lead to improved simulation results. The paper was submitted to JHE (ASCE), and has been accepted for publication (Storli and Nielsen, 2010). An online version of the un-copyedited paper can be found on the JHE web pages.

4.2 Paper B: A TWO-COEFFICIENT INSTANTANEOUS ACCELERATION BASED MODEL

This paper was the second paper to be made and submitted. Bearing the conclusion from the first paper in mind, a numerical scheme to simulate the water hammer transient using a MIAB model was made, allowing for the single coefficient used in the MIAB representation of head loss to be dependent on the position in the pipe. This approach was initiated by the observation that constant coefficient MIAB model simulations seemed to be unable to match peak pressures from experimental result for different positions in the pipe in the same simulation. A single position dependent coefficient was constructed, and the coefficient was shaped like the line for the absolute mean values for the friction loss presented in the Paper A. The results were surprising; the simulated peak pressures did not match experimental results, but the dynamical behaviour of the simulated pressure traces became much improved compared to the experimental results. Since the objective of the construction of the position dependent single coefficient was to match experimental peak pressure in a better way, the effect was then tested for different distributions of the coefficient. The result was that peak pressures were accurately predicted if the distribution of the coefficient was a rapidly decaying exponential function. However, this distribution of the single coefficient altered the dynamical behaviour of the simulated pressure trace in an unrealistic way. Therefore, the single coefficient was divided into two different coefficients, one for each of the derivative terms in the MIAB model. Since the local acceleration term is responsible for the non-dissipative phase shift in the simulations, the initially tested line shaped like the absolute mean value for the unsteady friction loss was used with the local acceleration. The spatial derivative term of the velocity is responsible for the dissipation in the model, so the rapidly decaying exponential function was linked to the spatial derivative term in the MIAB model. The simulated results showed an excellent congruency with experimental results, the degree of congruency with experimental results for an MIAB simulation had never, to my knowledge, been presented for the low Reynolds number water hammer investigated.

Originally, the submitted manuscript only contained the parts in Paper B that is concerning the simulations using the new position dependent coefficients. All reviewers were positive about its contributions. Before the comments from the reviewers were received, the manuscript for a third paper had been submitted. This manuscript investigated the effect that the position dependent coefficients had in the simulations. This manuscript was, at the request of reviewers and editors, incorporated in the revised version of the originally submitted manuscript that presented the position dependent coefficients.

4.3 Paper C: INVESTIGATION OF THE EIT MODEL BASED ON CURVED COEFFICIENT APPROACH IN MIAB MODEL

The third model applicable for practical purposes is the model based on Extended Irreversible Thermodynamics (EIT). This model was investigated by approximately translating the coefficients that highly improved the MIAB simulations presented in Paper B into the coefficient that needs to be determined for the EIT model. This translations showed that the post-calculated EIT coefficient T became position dependent, but more importantly that the coefficient became negative for certain periods of the transient for parts of the pipe. Simulations using this coefficient show that the behaviour of the simulated pressure trace is improved, although the negative coefficient implies that the model is being used outside its range of validity and violates assumptions in the development of the phenomenological equations in EIT formalism. In Paper C, this is being argued as a possible limitation to the EIT model that might not be just, considering the physical phenomena involved in the water hammer transient. The argument for this is that the EIT derivation of a phenomenological equation for unsteady friction uses the second law of thermodynamics where the time rate of entropy production arising from irreversibilities is utilized. This entropy production must be equal to, or greater than zero. The entropy production is zero for a reversible process and at equilibrium. This zero condition was originally used in Axworthy et al., (2000) as a necessary condition when the flow is zero, implying that the process is at equilibrium when the flow is zero. This implication seem not just when considering the velocity profile at zero flow, because local radial velocities are not zero and that kinetic energy contained within the velocity profile at zero flow is dissipated since the reversed velocities will reduce each other during the zero flow period.

5 CONCLUSIONS

A position dependency of the two-coefficient MIAB model has been found to significantly improve the simulations for a sudden closure of a downstream valve for initially low Reynolds number flow compared with experimental results. The main improvement is the fact that the dynamical behaviour of the pressure-time history using these coefficients is much more in accordance with experimental results than previously reported simulations from MIAB models using other coefficients.

The methodology in finding the position dependent coefficients are based on the unique periodicity for the occurrence of velocity gradients along the pipeline and the weighting function used in the convolution based models. Although two new constants have to be determined when finally deciding on the two coefficients, one can argue that the position dependent coefficients are, at least partly, based on physics. Much work is needed to see if this methodology is an improvement to the general water hammer transient phenomena, but the methodology seems to create position dependent coefficients that agree with reported behaviour when for instance initial Reynolds number or pipe length is changed. The methodology shows promise, although much work is needed before this novel approach can be confirmed to represent a general improvement.

This novel approach is not directly addressing one of the major limitations to the single constant coefficient MIAB model; it does not produce damping for valve opening scenarios. However, the approach of analysing the behaviour of the convolution based models for these scenarios might provide valuable and important information for the use as a basis for construction coefficients proper for these types of transient. This work would probably have to find time-dependent coefficients (dependent on direction of pressure wave propagation), since the MIAB model for time-invariant coefficients does not provide any unsteady damping no matter what the value for the coefficients are.

6 FUTURE WORK

The ultimate desire in this field of research is a comprehensive model applicable for pipe networks on arbitrary transient events and *a priori* in nature that is accurate and computationally inexpensive. This desire is not likely to be met in the near future, but hopefully the work presented in this thesis represents a novel approach that will contribute to a model or methodology that will make such a model obtainable. Future work should try to reveal if a methodology can be found for simulations of valve opening transients using the MIAB model. This is paramount for any model's applicability to pipeline systems. If the MIAB model is found to produce acceptable simulations for valve opening events, the next step would be to see if a methodology to find coefficients for general pipe networks and general transients can be developed. The use of the term "methodology" is deliberate; identical pipes would experience different transients dependent on the system they're a part of, so it is the system as a whole that would define the transient behaviour, thus also transient friction. Each specific pipeline system is likely to be governed by its own tailor-made unsteady model coefficients.

7 NOTATION

This is the notation for Part I: Summary. Each paper in Part II contains a separate notation.

ASCE	American Society of Civil Engineering	abbreviation
a	wave speed	[m/s]
CB	Convolution Based	abbreviation
D	pipe internal diameter	[m]
EIT	Extended Irreversible Thermodynamics	abbreviation
f	friction coefficient	[-]
g	gravitational acceleration	[m/s^2]
H	Piezometric head	[m]
h_f	head loss per unit length	[-]
IAB	Instantaneous Acceleration Based	abbreviation
JHE	Journal of Hydraulic Engineering	abbreviation
k	coefficient used in IAB models	[-]
L	pipe length	[m]
M	mach number	[-]
MIAB	Modified IAB	abbreviation
MOC	Method of Characteristics	abbreviation
NTNU	Norwegian University of Science and Technology	Norwegian abbreviation
T	thermodynamic coefficient	[-]
T_d	time scale of radial diffusion of vorticity	[s]
t	time	[s]
u	convolution time	[s]
V	bulk velocity	[m/s]
W	weighting function	[-]
x	space variable	[m]
1D	one-dimensional	appellation
2D	two-dimensional	appellation
$\Delta(\,)$	increment of property in parenthesis	[( )]
Γ	friction importance parameter	[-]
ζ	simulation time	[s]
υ	kinematic viscosity	[m^2/s]

Φ	sign-correcting coefficient	[-]
τ_W	wall shear stress	[kg/s^3]
ρ	fluid density	[kg/m^3]

Subscripts

0	denotes initial value
3	denotes coefficient in the original Brunone model
q	denotes quasi steady values
t	denotes coefficient used with local acceleration term in two-coefficient MIAB model
u	denotes unsteady values
x	denotes coefficient used with spatial derivative term in two-coefficient MIAB model

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Part II

Papers

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