Making the world a safer and better place – a plea for more data, validation cases and guidelines for waterhammer simulation

Trey Walters P.E.
Applied Flow Technology
Colorado Springs, Colorado, USA

G G Orieux, Q Li, L Thomson
Enbridge Pipelines Inc.
Edmonton, Alberta, Canada

13th International Conference on
Pressure Surges 2018
Bordeaux, France, 14th-16th November 2018

Making the world a safer and better place – a plea for more data, validation cases and guidelines for waterhammer simulation

T W Walters
Applied Flow Technology, USA
G G Orieux, Q Li, L Thomson
Enbridge Pipelines Inc, Canada

ABSTRACT

Engineers tend to overdesign systems when uncertainty exists. Overdesign is an important part of the engineering process, but unnecessary overdesign will only increase the cost of systems without enhancing safety.

An experience between a major pipeline company, their engineering design firm, and the waterhammer simulation software products used by both is described. A disagreement between software package results and ultimately the two companies developed into an issue that could significantly increase costs. More and better *validation cases* would have helped everyone navigate this situation more quickly, easily and inexpensively. More and better *application guidelines* may have helped the engineering design firm achieve higher certainty in their recommendations with potentially less overdesign.

NOMENCLATURE

DGCM	Discrete Gas Cavitation Model
DVCM	Discrete Vapor Cavitation Model
EPC	Engineering, Procurement and Construction company
MOC	Method of Characteristics
O/O	Owner/Operator

1 INTRODUCTION

“An expert is a person who has found out by his *or her* own painful experience all the mistakes that one can make in a very narrow field.”

– Neils Bohr

Italicized words added by the authors of this paper.

Fukishima in 2011. Deepwater Horizon in 2010. Hurricane Katrina (and the many failed pumping stations around New Orleans) in 2005. TWA Flight 800 (New York to France) in 1996. Piper Alpha offshore rig in the North Sea, in 1988. Apollo 13 in 1970, somewhere between the Earth and the Moon (subsequently called a “successful failure”).

Aside from Apollo 13, these spectacular failures had significant and tragic human, environmental and economic impacts. Some affected a large geographic area. All depended on safe and reliable fluid transfer systems which, for various reasons, failed. As engineers, it never hurts for us to remind ourselves of our failures and our responsibility to move our world towards safer and more reliable systems.

Over the last five to six decades, the progress in the ability to simulate waterhammer in piping systems is truly breathtaking. In the lifetime of some of our senior waterhammer experts, we have progressed from graphical methods (before digital computers) to today's visually interactive, menu-driven computational tools that run on laptop computers – e.g., see Ghidaoui et al., 2005 (1). This progress has been backed by broad research in computational methods as well as targeted research on transient behavior of piping system equipment and components such as pumps, check valves, air valves and relief valves.

One estimate is that there are more than two billion pumping systems in the world (Walters, 2014 (2)). It goes without saying that transporting fluids safely is of critical importance to today's world. However, one might reasonably ask if the number of fluid systems in the world is growing faster than our ability to develop and deploy pragmatic guidelines for how to properly analyze them. Related to this, and of equal importance, are guidelines for the tools used by engineers in the detailed design of often very complicated systems.

To be sure, this is not new information to the waterhammer community. Found in the literature are efforts to create:

- software standards (Baker and Ramos, 2000 (3))
- guidelines for benchmarking waterhammer software (Anderson and Bergant, 2008 (4))
- waterhammer guidelines for applications such as water distribution (Pothof and Karney, 2013 (5)), hydropower (Bergant et al., 2014 (6)), and nuclear power (Merilo, 1992 (7)), among others
- a centralized database for waterhammer software validation cases (van der Zwan et al., 2015 (8))

If it was easy to develop and implement, broad waterhammer guideline adoption would have already happened. But it is not easy. For at least three reasons:

1. The number of industries and applications is growing – The success of these efforts is complicated in part by the sheer number of industries and applications which need waterhammer guidance. It is very difficult even for top experts to be able to stay abreast of all the different issues that present themselves specific to each industry and applications within each industry.

2. The structure of how projects get completed is complicated – A typical project today involves an engineering firm who does the design, analysis, and construction. In some cases, a separate construction company is used. Once completed, they hand the system over to an owner/operator and then walk away. The owner/operator may not have much, if any, waterhammer expertise to guide design or operations. In some cases, government entities are also involved.

3. Waterhammer understanding is still progressing – Further complications involve progress in various technical aspects of waterhammer such as transient cavitation modelling, fluid-structure interaction and frequency dependent friction modelling. How do or should these be included in guidance to industry?

It can certainly be agreed that the first goal of the waterhammer community is the safe design and operation of fluid transfer systems. A second goal is that fluid transfer systems be economical to build and operate – which means avoiding unnecessary overdesign whenever possible.

The purpose of this paper is to discuss the two issues of safety and the economics of overdesign. A recent experience between Enbridge Pipelines Inc, Canada, a major pipeline company (an Owner/Operator, or O/O) and their Engineering, Procurement and Construction firms (EPCs) illustrates this issue. As the experience is related, it will be shown how yet more guidance is needed.

2 THE SOFTWARE TOOLS

Today there are a variety of commercial waterhammer simulation tools available (Ghidaoui et al., 2005 (1)). There are two software tools involved in this story. The first is the commercially available software developed by the first author's company, *AFT Impulse* – see Applied Flow Technology, 2016 (9). The second is another commercially available software tool not identified here.

The first tool is based on the Method of Characteristics (MOC). At the time of this experience with the pipeline company, the software had a single liquid column separation model (hereafter referred to simply as "transient cavitation" or just "cavitation"). This was the Discrete Vapor Cavity Model (DVCM). In part as a response to this experience, a second model, the Discrete Gas Cavity Model (DGCM) was implemented. But this story primarily involves the DVCM.

The second tool used a non-MOC solution method. It did have the ability to model transient cavitation, but since it was non-MOC, the cavitation model was not the DVCM or DGCM as we strictly know them. The software developer said it was "mostly based on DVCM".

By way of brief summary, the DVCM is considered to be the most simplistic of discrete multi-cavity models. It is a purely mechanical model and tracks vapor formation and collapse without any vapor equation of state or thermodynamics. The DGCM works on the basis of an equation of state and an always existent quantity of free air at each computing section. The free air changes volume with pressure. Each model takes an otherwise highly complex distributed vapor formation and collapse process and simplifies it into a discrete vapor formation at computing nodes with simplified physics. One result of these simplifications is that each model is susceptible to unrealistic and false pressure spikes. The DGCM is, on average, less susceptible to false pressure spikes and is generally regarded as the more accurate of the two. It can be shown that the DVCM is a limiting case of the DGCM. See Bergant et al., 2006 (10) for more on DVCM and DGCM. See Stewart et al., 2018 (11) for a guideline on identifying which spikes are false and which are real.

Without making any judgement on the merits, or lack thereof, of the MOC, the first tool will be called in this paper "the MOC tool". Since the second tool did not use the MOC, it will simply be called "the non-MOC" tool.

There was more than one EPC involved, but one in particular pursued this issue with more vigor. Focus will thus be given to this EPC. This company will just be called "the EPC". The major pipeline company will be called "the O/O".

The EPC had access to both tools but had a strong preference for the MOC tool. The O/O also had access to both tools but had a strong preference for the non-MOC tool. Both companies had waterhammer competency and had provided training on both tools to their staff.

Both tools have been commercially available and widely used for more than two decades. The MOC tool has been qualified by multiple companies with a nuclear verification and validation package (commercial grade dedication, or CGD) – e.g., see Archon Engineering, 2016 (12). The qualification of the non-MOC tool will not be discussed here for reasons of anonymity. But it was a capable, robust and trusted tool, especially by the O/O.

3 WHEN WATERHAMMER TOOLS AND COMPANIES DISAGREE

The experience behind this paper was not a single experience, but a sequence of experiences over several years. Most of the experiences happened between the EPC and the O/O (including, to varying degrees, the 2nd, 3rd and 4th authors). Both the EPC and O/O are customers of the first author's company, but the first author's company was not directly involved in many of the interactions between the EPC and O/O. It is fair to say the first author's company was drawn in by the nature of the enquiries received from the EPC and O/O. This included technical support, onsite training and numerous personal visits to each company by the first author and some of his colleagues. Suffice it to say that the situation was a complicated and evolving story that ended up progressing beyond engineering into the realm of liability/legal and perceived contractual risk. The way it be will described here may make it sound more straightforward and succinct than it really was. The essential elements will be summarized and cleaned up to communicate the important aspects of this illustrative story.

As mentioned already, the O/O was a pipeline company. Waterhammer simulation on pipelines was something in which they were experts. Besides the physical pipeline, there are other systems and aspects about which a pipeline company must be concerned. At a minimum, there are pumping stations and storage facilities. For some companies, there are delivery systems from and to liquid product processing facilities. For other companies, there are delivery systems from and to transportation hubs such as ships and rail cars. If the pipeline is offshore, then there are additional systems, issues and considerations. All of these have fluid transfer systems that are not directly part of the pipeline itself. And all of these have potential waterhammer issues.

This is also why some EPC or O/O companies may have more than one waterhammer simulation tool available to their staff. They may view one tool as better for the main pipeline simulation and a different tool as better for the facility piping simulation, for example. Better in this context does not necessarily mean more accurate. It can mean multiple things like the ability to communicate with customers or suppliers, ability to oversee work, ability to exchange data with other engineering or CAD tools in use, particular features such as better support for piping mechanical design, and the ability to more easily find experienced users in the marketplace.

There were several areas of concern between the EPC and O/O which included transient cavitation predictions, check valve behavior and relief valve behavior. The one that was most significant was transient cavitation and that is what will be focused on here.

A paper the first author recently co-authored (Stewart et al., 2018 (11)), would have been of significant assistance to both the EPC and O/O had it been available when this story was happening. The essential elements of that paper were communicated to both companies. But when projects are moving fast and have budgets and schedules, engineers are uncertain what to do in some cases. When that happens, engineers often recommend a result they believe is conservative.

In this case, engineers at the EPC were looking at transient pressure predictions at design conditions using the MOC software and encountered high predictive pressure due to cavitation within relief piping during a relief event. They were not sure what to make of some of these high pressures. They had been educated by the MOC software developer through lengthy technical support discussions and onsite training classes. But uncertainty remained. In some cases, the EPC could not conclusively rule out some of the high pressure predictions as inaccurate. Thus, they reported those pressures to the O/O along with supporting graphs of time histories and maximum pressure envelopes.

The O/O was aware that there were limitations of the non-MOC software but had very limited understanding of the limitations with MOC software in predicting transient cavitation. Now their EPC was recommending they design for higher pressures due to the predicted pressures from the transient cavitation calculation. The O/O company pushed back on their EPC's predictions and recommendations. They looked at the graphs from the EPC and plainly did not believe that the predicted high pressures were real. These two perspectives, design ranges versus operating reality, seemed to be at odds.

The EPC came to realize that their O/O customer was looking closely at the graphs in their reports and using that to dispute their analyses. But they were not ready to concede that the high pressure predictions were not valid. So, they decided to stop including graphs in their reports and just summarize peak pressures in tables. As one might easily guess, this made the O/O company even more suspicious of the EPC results and the MOC software that was used. They started to believe the EPC might be concealing things from them. This made the situation worse.

The O/O pushed for the EPC to use the non-MOC software which they trusted and had used for many years, building simulations for many aspects of their business. The EPC had used the non-MOC software and had questions about the history and validity of some internal factors for design considerations. The EPC had to assume legal liability for their work and installed system performance. They resisted doing this based on the non-MOC software results without appropriate back-up for the software factors.

The predictions from the MOC software for the systems under design were compared to the non-MOC software predictions. The results were different. The non-MOC software had lower and much smoother pressure predictions after cavities collapsed. The O/O believed the non-MOC software. The EPC, on the other hand, did not so much believe the MOC software as much as they disbelieved the non-MOC software.

Several things happened during the course of this experience. Of course, validation cases for transient cavitation were identified, modelled and compared (from several sources including Wylie and Streeter, 1993 (13)). Both software packages gave similar and valid results. Which was at once both encouraging and discouraging. It was encouraging that the two software tools agreed, but why did they disagree on the larger systems under design?

Additional test cases were constructed by the EPC in both software packages on simplified systems. These test cases were not backed by data but were conceptual in nature. One particular simplified test case became the focus and, while it was conceptual in nature, it included the basic elements of the type of systems the EPC was working on for the O/O. The results did not agree. The non-MOC software predicted much lower and smoother pressure variations on the conceptual test case. The first author's company's opinion was solicited. Having dealt with transient cavitation model predictions for two decades, the first author's company was aware of how uncertain they are in MOC software. But the smooth pressure variations in the non-MOC software did not look like anything they had ever seen. They just did not look right. The first author's company's only recourse was to point to the validation cases they had created against published cases. But the non-MOC software could equally match those cases.

If possible, the situation got even worse. The first author's company started to hear that the O/O was considering a ban of the MOC software from use on O/O projects. This would, in essence, force the EPC to use the non-MOC software which the O/O trusted. Nothing like this had ever happened before to the first author's company. From a commercial point of view this was obviously of concern. If it came to it, the first author's company felt they could tolerate the specific loss of business from the O/O and potentially the EPC. But the precedent was very uncomfortable and who knew where it could lead? Further, how could this happen to a software package which was trusted by many companies to, for example, model reactor safety systems in nuclear power stations in numerous countries around the world?

Before, during and after this experience, the first author and his colleagues were making regular visits to the EPC and, when it could be arranged, to the O/O. The O/O was straightforward about their problem with the MOC software and the disruption it was causing. To their credit, they were also open to new and updated information. The first author's company did their best to provide that information.

The EPC company continued to push on the conceptual test model which disagreed. Eventually they discovered something of significance. When transient cavitation occurred, the results changed in the non-MOC software test model if they added more computation nodes. In fact, the more nodes they added to the non-MOC software model, the more the non-MOC software results started to look like the MOC software results. On the other hand, adding more nodes to the MOC software model did not change its predictions in any significant way (this is typical of MOC-based software – see Bergant et al., 2006 (10)). Eventually the EPC got the conceptual test model to more closely agree – after they added enough nodes to the non-MOC software test model.

During this process the MOC software developer was working hard on implementing the DGCM into the software. This had been in progress previously but took on added importance because of this situation. This took many months and had its own quality of results issues. But eventually this was completed. Having both DVCM and DGCM models in the software gave additional ability to the engineers when they attempted to interpret pressure predictions and recommend peak pressures for design.

Certainly, part of the cause of problems like the one in this paper is caused by an issue raised in the Introduction. This relates to how projects get completed with an O/O and a separate EPC. When an EPC is asked to design, analyze and build a system, and contractually must take on liability, the answer to the question on who makes the definitive decision on recommended design pressures is ambiguous. The EPC must design, analyze and build. The O/O must approve the design and analysis. The O/O pays. The EPC has the liability. The definitive answer depends on how much risk the EPC thinks they are exposed to and how much expense the O/O will tolerate. When the two sides no longer can agree on how to balance these, the business relationship may very well terminate.

The situation in this paper eventually came to a peaceful conclusion. The MOC software ban did not happen. The O/O incorporated some hardware modifications to their relief valve selections to minimize transient cavitation and were thereby able to accept their EPC recommendations based on the MOC software predictions. An improved relationship was built between the MOC software company and the O/O. And hopefully everyone involved learned something constructive from the experience, especially when considering the design requirements compared to operating ranges.

This brings up a question, though. What might have been done differently to have avoided this situation in the first place?

It also brings up a question that industry may want to seriously consider in its quest for safe and economical designs. With the many uncertainties that still impact waterhammer simulation, perhaps employing two simulation tools is the wisest approach?

4 MAKING THE WORLD A SAFER AND BETTER PLACE: MORE AND BETTER DATA AND GUIDELINES

In a perfect world, situations like the one just described could be avoided. Perhaps the best we can hope today, considering the state of waterhammer simulation technology (as amazingly advanced as it is), is that such a situation can be more quickly, easily and inexpensively navigated.

If progress is to be made, then still more collaboration between academic experts, industrial application (and field-based case studies), and simulation tool developers is essential. As summarized earlier, others have made valuable and significant contributions towards this end (References 3-8). It is not clear to the authors that these previous efforts, if they had been fully implemented and adopted by industry (which, to the authors' knowledge, they haven't – except perhaps in nuclear power), would have been sufficient to avoid the experience of the EPC and O/O in this paper. It may be the case that there is no way to avoid such situations. At least not completely. And not with today's technology and tools. However, the authors do believe that certain improvements can at least help.

4.1 More and better guidelines

Some industries have made significant progress in the areas of broad, waterhammer guidelines. As mentioned earlier, these include water distribution (5), hydropower generation (6) and nuclear power generation (7). Efforts from academia, industry, engineering societies, standards bodies and governments are needed to make these as effective as possible.

Some topical guidelines exist and are extremely valuable. A recent proposed topical guideline by the first author (Stewart et al., 2018 (11)) for taking waterhammer transient cavitation results and deciding on pipe structural design safety factors has been offered. Hopefully this proposed guideline will receive scrutiny and critique and can be the beginning of an accepted and effective guideline for practicing engineers on this topic. The first author is aware of many engineers and companies in industry who wrestle with this issue and have difficulty finding guidance which they can rely upon. More topical guidelines like Stewart et al. are desperately needed.

In some cases, methodology exists but is not developed far enough. The first author is thinking of how his company struggled in implementing the DGCM in their MOC software. The methodology for basic, mostly single pipe systems, exists. But taking that across an open valve, for example, which might be changing position with time, is very complicated and fraught with potential errors in basic methodology and software coding. The first author attempted to develop an analytical expression for the DGCM open valve which resulted in a 16th order polynomial and an algebraic equation with roughly 100 cross terms. Neither Mathcad nor Mathematica were able to solve for the roots – 16 of them! Even though it was, in principle, simple algebra, the opportunity for calculation errors in the basic formulation of the open valve equations were numerous.

Eventually, an iterative method was developed but still required judgement on how to handle many cases. In the end, a recognized expert was engaged to give his independent consideration of the MOC software implementation and results. The first author's company simply had no other way to verify that their implementation was correct. Some published theory and expected numerical results for open valves would have been most welcome. There are other pipe system configuration elements that face similar issues. The expert engaged by the MOC software company assisted with these as well.

Bringing this into more clarity, it is not just the issue of saved effort and expense when addressing DGCM and open valves that is of importance. The reader is reminded that the MOC software discussed here and others like it are used to ensure safe design and operation of many types of fluid transfer systems, including those in nuclear power stations as described earlier. Having published descriptions on the methods and mathematics at the detailed level will only help all parties including end users.

4.2 More data and validation cases

Anderson and Bergant, 2008 (4) provide a very well thought out and comprehensive treatise on waterhammer software benchmarking. Many of the issues they raise may never lend themselves to a pragmatic solution, which they acknowledge. But the direction and framework they provide is excellent. Van der Zwan et al., 2015 (8) propose a web-database of validation cases. This also is an excellent proposal which will hopefully gain favor and move towards reality.

Even with these elements in place, the authors do not believe they would have helped avoid the experience discussed in this paper. The authors see three extensions to van der Zwan et al., 2015 (8) that would be beneficial and would have helped.

4.2.1 Geometrically larger system cases

Most of the validation data we all use today are necessarily based on lab-scale geometrical configurations. This typically means pipes of shorter length and smaller diameters, pumps with lower power and valves of smaller size. Those that present results for longer pipe lengths often have no choice but to use pipe coils or systems with many bends in order to fit inside lab buildings.

As we all are aware, many of the systems where waterhammer must be considered are much larger than lab scale. One can perhaps hope one day for lab buildings many kilometers in length where more tests can be performed. More pragmatically, the authors recommend that some category of validation be included which includes systems of larger geometric scale.

The following two sections expand this recommendation. Before moving to those, the authors will clarify the reason for this based on the experience described in this paper. The MOC and non-MOC software both gave comparable results when compared to the standard lab scale validation cases for transient cavitation such as those collected in Wylie and Streeter, 1993 (13). However, when a conceptual test case was developed which was kilometers in length rather than lab scale, the two software packages no longer agreed. Hence a validation case of larger geometry would certainly have helped.

4.2.2 Inclusion of field data cases

Unless we are going to build lab buildings kilometers in length, then the only source of real world data for large systems will come from field studies. Anderson and Bergant, 2008 (4) discuss in great detail the issues and limitations of field data use for validation. Nevertheless, that will likely be the only source of data for geometrically larger systems. Hence it is recommended a category for field data be included in the van der Zwan et al., 2015 (8) web-database. A caveat may be required that the data is less precise and, perhaps, less trustworthy than tightly controlled lab data. But at least the data is there and vetted by the web-database committee of experts.

4.2.3 Numerically generated verification cases

Anderson and Bergant, 2008 (4) warn of the pitfalls of basing validation on previously generated numerical results rather than physical tests. They argue that such a process belongs more properly in the category of verification (see Anderson and Bergant for a thorough discussion of the differences). Even so, having some outlet for collecting numerically based verification cases for software tool developers and independent users (often coming from an industrial company performing due diligence on engineering software) will at least provide an option that otherwise would not exist.

The discussion earlier about the DGCM across an open valve, possibly itself changing position, is a good example of this. There are many sub-cases that occur and have to be addressed in code. In some cases, the proper approach is ambiguous and the mathematics not trivial. Having numerically generated results for each case, in step-by-step numerical format, would help the quality of software implementations.

4.3 Recognition of completeness of validation cases

This issue of completeness in validation cases is a regular frustration at the first author's company when attempts are made to perform validation. Many excellent papers and research are published without sufficient data to recreate the original lab or field system. Certainly, this is due in part to space limitations from publishers. Further, the amount of data required to truly recreate the system and related transients can be substantial.

Nevertheless, if we are going to have better sources of software validation, it is essential. A published study which lacks information on pipe steady friction or wavespeed, tank levels, pump data, valve Cv, elevations at all points (especially where cavitation occurs), valve transient profiles, etc., is not useful for validation.

One example of this the first author's company experienced was trying to reconstruct some of the excellent experimental results from a prominent waterhammer expert's PhD thesis (Simpson, 1986 (14)). Two different smart, young engineers spent substantial time trying to reconstruct the system used in the experiments without success because of incomplete or ambiguous information.

The authors recommend a recognition system be adopted where for a particular study, be it lab-based, field-based or numerically-based, completeness of data is recognized by a community of experts. Perhaps a preliminary, second level of completeness can be included where the author of a study can claim completeness. This claim is just the author of a study saying that all data exists in the paper to reproduce the results. The community of experts can then evaluate all claims of completeness and then, subject to review, elevate the study to a first level of recognized completeness.

To this end, the first author has authored or co-authored two other papers at this conference with the intent of providing complete data to reproduce the results. See Lozano, Bosch and Walters, 2018 (15), a field study, and Walters, Lang and Miller, 2018 (16), a numerical study. With the second study, substantial supporting and secondary data was generated and not included in the published study due to space limitations and information not being pertinent to the main focus of the paper. Recognizing this, these papers have collected all supporting data into support documents (mostly Excel and PDF files, including pump manufacturer data sheets for pumps used in the study) and have provided these for easy access and download to others who wish to explore the results further. Leveraging modern information technology to disseminate such supporting information seems like a good idea.

With this in mind, the van der Zwan et al., 2015 (8) web-database might be improved if it allowed an author to upload additional supporting information for a study used for validation and verification purposes.

Finally, not all studies lend themselves towards validation or verification. This can be for numerous reasons including the system being just too complicated and/or having too many operational cases for an author to be able to thoroughly document it in a paper of 10-15 pages length. A second reason is that the underlying system is proprietary, or the location is anonymous due to lack of permission from the system owner to publish it in detail.

4.4 Some thoughts on the cost of obtaining validation data

Performing experimental testing can be difficult and expensive. One of the cost advantages of field tests is that the data is obtained for other purposes related to a commercial project. Hence the expense of obtaining the data for validation purposes is negligible. It is already there. The main expense then becomes the authors' time in getting permission to publish the data and then getting the field data into a publishable form. This is another reason to increase openness to field studies in the van der Zwan, 2015 (8) database.

4.5 Forum for debate, critique and feedback from stakeholders

The authors also see value in the van der Zwan et al., 2015 (8) database for offering a web-based forum for debate, critique and feedback from stakeholders on each validation case. In this case stakeholders include the study authors, the community of experts who vet the database, software developers perhaps unrelated to the original study, and any entity attempting to use the database for independent validation and/or verification of a software package.

This may take the form of a thread on each database validation case where discussion is archived and participants who post to the forum must identify themselves. No anonymous posting should be allowed. Anonymous viewing of the forum should be allowed in the authors' opinion. An active forum moderator would be advisable.

4.6 Some thoughts on a web-database development

There are of course many potential options for creating such a database. There may well be an equal number of obstacles. Who pays? Who decides? Who manages?

One such potential avenue is with a consortium approach like that used by the Pipeline Research Council in Canada (17). The model used is likely familiar to many of us. An example today is how PRCI is funding new research into fluid viscosity effects on centrifugal pump performance. It is an area of common interest to many industrial players, so they co-operated to fund that initiative.

Another possible avenue is with a trade organization like the Hydraulic Institute (18). Over the last two decades HI has expanded its focus from pumps to include pumping systems. Among other things, HI creates standards. It does so not just for pumps but also for data, see HI 50.7-2010 (19). Further, HI has already created a web database for pump issues such as energy ratings with their ER Program Portal (20). Perhaps an organization like HI can be approached to host a database?

A final thought on the question of "who pays?" can be directed to O/O companies. In this paper the O/O incurred expenses in part because of software trust and validation issues. Perhaps more O/O companies can be persuaded that, rather than spending money on working through problems with their EPCs, perhaps an equal or maybe lesser amount of money could be directed towards a web-database of validation cases. Perhaps this paper can help explain why they should consider this.

4.7 Continued and expanded engagement with standards bodies

Standards bodies have the ability to create guidelines that can be eventually codified into regulations and even law. Many of the community of waterhammer experts are involved in, or have awareness of, what is happening in standards bodies. Due to the breadth of industries where waterhammer is important, as well as international interest, standards development is complicated by the number of organizations. It seems doubtful that a single standard could ever be developed that would apply across all industries and nations. But that does not mean it should not be attempted. Where a single standard is not possible, more focused industry and national standards would be of great help.

4.8 How far does software validation need to go?

Ultimately the answer to this question resides with the engineers who use the software, analyze the systems, and produce designs and operating guidelines. Good engineers can often overcome uncertainties in software by carefully choosing their assumptions and building conservatism into their analyses. When such conservatism leads to conflicts like that in this paper, validation cases can help.

5 CONCLUSION

Many previous authors have made bold calls for improved guidelines for waterhammer simulation. This includes validation and verification of simulation software.

An experience between an EPC, an O/O (2nd, 3rd and 4th authors) and a software tool developer (the 1st author) reaffirms the need for more and better guidelines and more data. Some of the unique aspects of this experience points to additional considerations that guideline creators may wish to address in the future. The authors hope the end result of addressing these issues is that industry can build and operate fluid transfer systems that are safer and better.

6 ENBRIDGE DISCLAIMER

Any information or data pertaining to Enbridge Employee Services Canada Inc., or its affiliates, contained in this paper was provided to the authors with the express permission of Enbridge Employee Services Canada Inc., or its affiliates. However, this paper is the work and opinion of the authors and is not to be interpreted as Enbridge Employee Services Canada Inc., or its affiliates', position or procedure regarding matters referred to in this paper. Enbridge Employee Services Canada Inc. and its affiliates and their respective employees, officers, director and agents shall not be liable for any claims for loss, damage or costs, of any kind whatsoever, arising from the errors, inaccuracies or incompleteness of the information and data contained in this paper or for any loss, damage or costs that may arise from the use or interpretation of this paper.

7 REFERENCES

(1) Ghidaoui, M. S., Zhao, M., McInnis, D. A. and Axworthy, D. H., (2005), "A Review of Water Hammer Theory and Practice", *Applied Mechanics Review*, 58(1), pp. 49-76.

(2) Walters, T. W., (2014), "Opportunities and Barriers In Applying Optimization To Reduce Energy Use in Pumping Systems", Keynote address, *VR&D User Conference*, Monterey, California, USA, Oct 2014, https://www.vrand.com/sites/default/files/pub/VRD-2014UConf_TWalters_Keynote1_AFT.pdf

(3) Baker, P. J., and Ramos, H, (2000), "Selection of Transient Analysis Software for Pipeline Design: Towards a European Standard", *Proc. 8th International conference on pressure surges*, BHR Group, The Hague, The Netherlands, April 2000.

(4) Anderson, A. and Bergant, A., (2008), "Issues in 'benchmarking' fluid transients software models", *Proc. 10th International conference on pressure surges*, BHR Group, Edinburgh, UK, May 2008, pp. 519-537.

(5) Pothof, I. and Karney, B., (2013), "Guidelines for Transient Analysis in Water Transmission and Distribution Systems", *IntechOpen*, www.intechopen.com/books/water-supply-system-analysis-selected-topics/guidelines-for-transient-analysis-in-water-transmission-and-distribution-systems

(6) Bergant, A., Karney, B., Pejovic, S., and Mazij, J., (2014), “Treatise on water hammer in hydropower standards and guidelines”, *27th IAHR Symposium on Hydraulic Machinery and Systems* (IAHR 2014).

(7) Merilo, M., (1992), “Water hammer prevention, mitigation, and accommodation”, *EPRI NP-6766*, Project 2856-03, Final Report (6 Volumes), Electric Power Research Institute, Palo Alto, USA.

(8) Van der Zwan, S., Heinsbroek, A., Tukker, M., Karney, B., and Bergant, A., (2015), “Water hammer software performance analysis and validation via a web-database” *Proc. 12th International conference on pressure surges*, BHR Group, Dublin, Ireland, Nov 2015, pp. 149-155.

(9) Applied Flow Technology, (2016), AFT Impulse 6, Colorado Springs, Colorado, USA.

(10) Bergant, A., Simpson, A. R. and Tijsseling, A. S., (2006), “Water hammer with column separation: A historical review”, *Journal of Fluids and Structures*, 22, 135-171.

(11) Stewart, M., Walters T. W., Wunderlich, G. and Onat, E. A., (2018), “A Proposed Guideline For Applying Waterhammer Predictions Under Transient Cavitation Conditions Part 1: Pressures”, *ASME PVP Conference*, Prague, Czech Republic, July 2018, ASME PVP2018-84338.

(12) AFT Impulse Nuclear Verification and Validation – Commercial Grade Dedication (CGD), Archon Engineering, www.archonengineering.com/nuclear-vv/

(13) Wylie, E. B. and Streeter, V. L., (1993), *Fluid Transients in Systems*, Prentice Hall, Englewood Cliffs, NJ.

(14) Simpson, A. R., (1986), “Large water hammer pressures due to column separation in a sloping pipe,” PhD thesis, University of Michigan, Ann Arbor, Mich.

(15) Lozano Solé, D., Bosch Segarra, R., and Walters, T. W., (2018), “Surge Transients Due To Check Valve Closure In a Municipal Water Pumping Station”, *Proc. 13th International conference on pressure surges*, BHR Group, Bordeaux, France, Nov 2018.

(16) Walters, T. W., Lang, S. A, and Miller, D. M., (2018), “Unappreciated Challenges In Applying Four Quadrant Pump Data To Waterhammer Simulation Part 1: Fundamentals, and Part 2: Application Examples”, *Proc. 13th International conference on pressure surges*, BHR Group, Bordeaux, France, Nov 2018.

(17) Pipeline Research Council, www.prci.org

(18) Hydraulic Institute, www.pumps.org

(19) HI 50.7-2010 Standard, http://pumps.org/uploadedFiles/Content/StandardsGuidebooks/Electronic_Data_Exchange/50-7.pdf

(20) ER Program Portal, http://er.pumps.org/ratings/home