A Proposed Guideline For Applying Waterhammer Predictions Under Transient Cavitation Conditions

Part 1: Pressures

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ABSTRACT

Waterhammer analysis (herein referred to as Hydraulic Transient Analysis or simply "HTA") becomes more complicated when transient cavitation occurs (also known as liquid column separation). While standard HTA transient cavitation models used with analysis based on the Method of Characteristics show good correlation when compared to known test/field data, the great majority of test/field data are for simple systems experiencing a single transient. Transient cavitation in more complicated systems or from two or more independently initiated transients have not been validated against data.

Part 1 of this paper describes the various safety factors already provided by ASME B31.3 for pressure containment, provides criteria for accepting the results of HTA calculations that show the presence of transient cavitation, and makes recommendations where the user should include additional safety factors based on the transient cavitation results.

Situations are discussed where waterhammer abatement is recommended to reduce hydraulic transient pressures and forces, and for increasing confidence in HTA results in specific cases. The result is a proposed comprehensive and pragmatic guideline which practicing engineers can use to perform waterhammer analysis and apply pressure predictions to pipe stress analysis.

KEYWORDS

water hammer, fluid transient, hydraulic transient analysis (HTA), transient cavitation, liquid column separation, ASME B31.3, Discrete Vapor Cavity Model (DVCM), Discrete Gas Cavity Model (DGCM)

OVERVIEW

An essential purpose of HTA is to provide guidance so the effects of transients can be accounted for in the piping system's structural design. It is frequently the case that HTA Engineers and Pipe Mechanical Design Engineers (or Pipe Stress Engineers) work in separate departments and, to some degree, speak a different "engineering language."

Among the things that HTA Engineers are concerned with is the prediction of fluid pressures and assessing their confidence level in those predicted pressures. Pipe Mechanical Design Engineers need to translate the HTA predicted pressures and their understanding of HTA confidence levels into pipe loads and safety factors used in pipe stress analysis.

A recent project at a nuclear facility in the USA led to a collaboration between the authors. While ASME piping codes provide guidance on safety factors, very little guidance exists for applying them to waterhammer conditions. Safety and piping integrity was a significant concern for this project as the fluids were radioactive.

The collaboration involved bringing together HTA Engineers and Pipe Stress Engineers to create criteria for accepting HTA results. The HTA Engineers documented these criteria in a software validation report. One of the unique aspects of the collaboration was that it involved not only the engineering design firm but also the developer of the HTA software.

The engineering design firm needed pragmatic guidance on how to interpret and apply HTA predictions. One issue that is especially challenging in HTA is modeling transient cavitation (frequently called liquid column separation). Transient cavitation occurs when a waterhammer pressure wave reduces the pressure in a pipe system to the fluid's vapor pressure. It is well known in the HTA community that the state-of-the-art transient cavitation models have numerous limitations and weaknesses. Among the many weaknesses is that there is a tendency for the models to generate non-physical pressure predictions which are unrealistic and, in some cases, completely inaccurate. The challenge in creating the document was to provide pragmatic guidance on how to interpret transient cavitation, what can be ignored as inaccurate, how to rank the confidence level of various predictions, and what safety factor should be used in the pipe stress analysis based on the confidence levels.

After this collaboration, the authors felt that the final document would be of interest to the larger engineering community. The purpose of this paper is to share the results of our collaboration and propose it as a guideline to be used by others facing similar challenges as those faced by the authors.

Considerable judgment was required in assembling the guideline we are proposing. The authors' driving purpose was to create something pragmatic and actionable. In an area as uncertain as HTA with transient cavitation, this required some difficult decisions on ambiguous issues. As a result, there is ample room for debate and disagreement, which the authors welcome. Engineers wishing to use these criteria should consider following the requirements of ASME B31.3 Para 300 (c)(3) [1].

The HTA software used, *AFT Impulse*, is commercially available and discussed in Applied Flow Technology [2] and Ghidaoui et al. [3]. It utilizes the Method of Characteristics (MOC) to solve the governing equations (Wylie and Streeter [4], Chaudhry [5]). While it is a general commercial HTA tool, it has a pedigree in the nuclear industry and has undergone nuclear commercial grade dedication (CGD) by various users. It includes the two most popular and well understood transient cavitation models – the Discrete Vapor Cavity Model (DVCM) and the Discrete Gas Cavity Model (DGCM). These models are documented in the literature (Wylie and Streeter [4], Bergant et al. [6]).

The guideline proposed in this paper applies most directly to MOC-based waterhammer software and designs which apply ASME piping code. The authors have made their best effort to generalize the internal document we developed into this guideline to make it as widely applicable as possible. The structure we have created here should prove useful and adaptable to situations which do not use MOC software or ASME piping code.

The guideline consists of the following sections 1.0-5.0. Later in this paper, after concluding the proposed guideline, the authors discuss some of the reasoning behind the decisions they made.

NOMENCLATURE AND SYMBOLS

S	Allowable stress
S_{hta}	Stresses due to the pressures calculated by HTA
S_{ut}	Tensile Stress at Temperature
S_{yt}	Yield Strength at Temperature

ABBREVIATIONS

CAC	Cavitation Acceptance Criteria
CSF	Cavitation Safety Factor
CSM	Cavitation Safety Margin
CVR	Cavitation Volume Ratio
DGCM	Discrete Gas Cavity Model – a model used in waterhammer analysis to simulate the formation and collapse of vapor cavities
DVCM	Discrete Vapor Cavity Model – a model used in waterhammer analysis to simulate the formation and collapse of vapor cavities
HGL	Hydraulic Grade Line
HTA	Hydraulic Transient Analysis (waterhammer analysis)
HTF	Hydraulic Transient Forces (imbalanced forces on piping that occur as a result of waterhammer)
MOC	Method of Characteristics
SF	Safety Factor
SM	Safety Margin
SME	Subject Matter Expert

1.0 GUIDELINE INTRODUCTION

While the Method of Characteristics (MOC) analysis for waterhammer using DGCM and DVCM transient cavitation models show good correlation when compared to known test/field data, the great majority of test/field data are for simple systems experiencing a single transient.

Transient cavitation results from systems with branching or network flow, elevation changes, area changes and various junction types have not been fully validated against data. Further, transient cavitation resulting from two or more independently initiated transients has not been fully validated against data.

To account for this uncertainty, cavitation safety factors are incorporated into the maximum calculated transient pressures based on the extent of transient cavitation (hereafter referred to more simply as "cavitation"). This criterion follows best practices used by the authors and requires the use of judgment by the user. In the end, the results should seem reasonable according to the judgment of the HTA Engineer.

This guideline describes the various safety factors already provided by ASME B31.3 for pressure containment, provides criteria for accepting the results of transient calculations that show the presence of cavitation and makes recommendations where additional safety factors should be added by the user based on the cavitation results.

2.0 DEFINITIONS

Alternatives – Where HTA cavitation results are found to be unreliable, adding abatement equipment to reduce cavitation to acceptable levels is the preferred solution. Other alternatives include analysis in other software with more robust mixed phase analysis capabilities such as RELAP5 [7] or a Computational Fluid Dynamics (CFD) system.

Apply Abatement – Abatement such as slowing valve closure, adding vacuum release valves, hydropneumatic tanks, battery backups, and pump flywheels, or restricting flow to raise HGL, are all possible, as is increasing the pipe pressure rating.

Cavitation Volume Ratio (CVR) – The ratio of cavitation vapor volume in a particular pipe segment to the computing volume of that pipe segment.

Note that the CVR typically changes with time for each pipe computing segment when cavitation occurs. The maximum CVR is of interest as it impacts the reliability of the simulation results not only at that computing segment but in all computing segments which communicate over time with that segment. Typically, this means the entire pipe system. Hence a new term is defined as:

Cavitation Volume Ratio Maximum (CVR_{MAX}) – The maximum of all CVR values for all pipe computing segments over all time steps of the simulation. This value is used to determine acceptance criteria and is categorized as:

None: Cavitation never occurs ($CVR_{MAX} = 0$)

Limited: $0\% < CVR_{MAX} \leq 10\%$

Major: $10\% < CVR_{MAX} < 100\%$

Extreme: $100\% \leq CVR_{MAX}$

Henceforth in this document, to distinguish between normal language usage of the preceding words and the usage in the present context of CVR severity, the words **None**, **Limited**, **Major,** and **Extreme** are bolded and capitalized when used in the present context.

The reader is cautioned not to place too much emphasis on the particular words we chose for these various CVR categories. We need words to which we could refer to later for decision-making purposes. For example, the word **Limited** should not be construed to mean that the cavitation is not significant. It can be very significant as is all cavitation.

DGCM vs. DVCM – The Discrete Gas Cavity Model (DGCM) and Discrete Vapor Cavity Model (DVCM) are two different mathematical models for simulating waterhammer transient cavitation. The DVCM is the older model and simpler in concept and in software implementation. The DGCM is typically the more accurate of the two and less susceptible to numerical model noise (see definition below). The DVCM is significantly faster computationally when cavitation is not occurring. It is thus the preferred default model. The DGCM should be considered once cavitation has been identified.

Localized vs. Extensive Cavitation – Localized cavitation means that cavitation tends to occur only in a local and a relatively small section of the system. Extensive cavitation means that cavitation occurs along the majority of a pipe and potentially in many parts of the system.

Numerical Model Noise – Pressure spikes that only last for one or a few time steps and/or are very sensitive to small changes in model input parameters that are a mathematical anomaly of the calculation (i.e., artifact of the cavitation model). These do not represent conditions that would occur in the real world.

Persistent Cavitation – Cavitation occurs at one or more locations and never stops during the transient simulation. This indicates that part of the system never repressurizes in such a way as to collapse the vapor. The presence of this condition can be checked by running a single-phase steady-state simulation of the system that represents the final system state after all transients have died out. If this steady-state simulation shows pressures below vapor pressure, then persistent cavitation in the preceding transient simulation definitely exists. Examples include cavitation at pump intakes, valves, or elevation high points during steady-state flow. Persistent cavitation represents sustained two-phase transient flow and is beyond the capabilities of most HTA software including the one used for this project.

Sectioning – The Method of Characteristics (MOC) requires that each pipe is broken up into smaller sections of equal length. This typically results in round-off errors in order to enforce a common time step size. One common way of accounting for the round-off error is to adjust the wavespeed in each pipe. Two options are available when selecting the proper sectioning.

1. **Minimal acceptable number of sections** – The least number of pipe sections that provide less than ±15% wavespeed round-off error in all transient model pipes; this is to be used only for evaluation of CVR and is not for use in determining HTA pressures or forces.

2. **Optimized sectioning** – A tradeoff between runtime and wavespeed error with less than ±10% wavespeed round-off error.

Sensitivity Check – Actions where the HTA model is modified to compare results from different inputs. Examples include 1) Changing cavitation model or turning cavitation off altogether, 2) Changing the model pipe sectioning, 3) Changing the model input data; e.g., changing by ±1% the liquid density, vapor pressure, boundary condition pressures, valve Cv, etc.

Similar/Consistent Results – When pressure spikes occur at a similar magnitude, timing, and duration. Similar here means the most significant pressure spikes are within 10-20%. Use judgment when comparing two runs on whether results appear similar. HTA cavitation models are imprecise, and general similarity is the best that can be expected when comparing runs.

SME – Subject Matter Expert (e.g., the Responsible Hydraulic Transient Engineer or a consultant).

3.0 SAFETY FACTOR / SAFETY MARGIN

Very Large – 200% Safety Margin or 3:1 Safety Factor against rupture

Large – 100% Safety Margin or 2:1 Safety Factor against rupture

Moderate – 50% Safety Margin or 1.5:1 Safety Factor against rupture

Small – 25% Safety Margin or 1.25:1 Safety Factor against rupture

Henceforth in this document, to distinguish between normal language usage of the preceding words and the usage in the present context of safety factor/safety margin magnitude, the words **Very Large**, **Large**, **Moderate** and **Small** are bolded and capitalized when used in the present context.

Pipe rupture due to pressure stress higher than the yield strength and less than the tensile strength of the material is a process that takes some time. Infrequent, very short duration events within the tensile strength limits of the material are not expected to cause rupture. Transient pressure spikes due to cavitation collapse that move through a system and never expose a section of pipe to pressure for more than a tiny fraction of a second are a prime example of this. For example, a pressure wave traveling thru a pipe at 4,000 feet per second (1,220 m/s) only remains in a 1-inch (2.5 cm) segment of pipe for 20 microseconds. These events are different from numerical model noise as the pressures persist for more than one or a few time steps and do not stay in the same place for more than one or a few time steps.

While calculated pressures should be kept within ASME B31.3 required limits, the safety factor that exists when very short duration pressure spikes are present can be based on a comparison to the tensile strength of the material. For pressures that endure longer than the passing of a pressure spike or occur during normal operations, bursting can occur when hoop stress becomes higher than the yield strength of the material. The frequent occurrence of pressure above the piping material's yield strength could lead to progressive distortion of the piping and eventually burst or even fatigue cracking, so this should not be allowed. Examples of longer-term pressures include operating conditions, pump deadhead, elevation pressures, line pack, and Joukowsky head. In such cases, safety factors must be based on a comparison to yield strength of the material.

For ordinary pressures such as pump operating pressure and transients caused by pump starts and stops, and valve movement, higher safety factors are recommended based on the rules in ASME B31.3. For less frequent events such as pump or control system malfunction, limited occurrence reduces the risk of failure; the "Occasional Variations Above Design Conditions" rules in ASME B31.3 302.2.4 allow for a higher allowable stress and therefore a lower factor of safety.

It would be excessive to stack safety factors for calculation uncertainty on top of safety factors built into the piping code. When the piping material specification is based on piping code rules that mandate a safety factor equal to or higher than the safety factor recommended for HTA output, and HTA calculates pressures within the pipe material specifications limit, then no additional safety factors need to be applied.

Application of overpressure rules must carefully consider the short-term pressure capability of various inline components. Where pressure external to the piping system is expected to exceed pressure inside of the piping system, the piping should be designed to handle the minimum pressure predicted by the HTA calculation decreased further using a **Small** safety factor or the fluid vapor pressure, whichever is higher.

The following guidelines apply to the most common piping materials used in ASME B31 Code applications. Specifically, additional consideration would be required for applications involving special high yield materials where yield is more than ½ tensile, or where temperatures are above the creep range of the material. Where these guidelines refer to pipe material specification limits, those limits are to be based on the standard ASME B31.3 rules for allowable stress Para. 302.3.2.(d).1 thru 302.3.2.(d).3. Symbology in formulas is based on ASME B31.3 Appendix J, except for S_{hta} which is introduced here to represent stresses due to the pressures calculated by HTA, and S_{ut} which is introduced here to represent Tensile Stress at Temperature. Per ASME B31.3, S is allowable stress, and S_{yt} is yield strength at temperature. Cavitation Safety Margin (CSM) or Cavitation Safety Factor (CSF), as used below, refer to safety margins or safety factors recommended by Section 5.0 "Specific Guidelines" of this document to address uncertainty in results from HTA that include cavitation.

3.1 Calculated pressures within pipe material specification limits per ASME B31.3 Para. 302.3.2.(d); $\boldsymbol{S_{hta} \leq S}$.

a. Very Short-Term Pressure – Limits are based on Tensile Stress (pressure spikes moving through the pipe and only exposing a particular location to the pressure for an HTA time step or a small fraction of a second).

   i. **If a 200% CSM (3:1 CSF) and lower is required**; a 200% Safety Margin is provided by ASME B31.3, so no additional modifications to pressure are required by the HTA Engineer ($S_{hta} \leq S \leq \frac{1}{3}S_{ut}$).

b. Longer-term Pressure – Limits are based on Yield Stress

   i. **If a 100% CSM (2:1 CSF) is required**; only a 50% Safety Margin is provided by ASME B31.3, so additional consideration is required by the HTA Engineer. Compare calculated pressures to 75% of the pipe material specification limits; alternately the same results are obtained by multiplying calculated pressures by 133% and comparing the resultant with unmodified pipe material specification limits ($S_{hta} \leq 0.75S \leq \frac{3}{4} * \frac{2}{3}S_{yt} \leq \frac{1}{2}S_{yt}$).

    - ii. **If a 50% CSM (1.5:1 CSF) and lower is required**; a 50% Safety Margin is provided by ASME B31.3, so no additional pressure safety factors are required by the HTA Engineer ($S_{hta} \le S \le \frac{2}{3} S_{yt}$).

3.2 Calculated pressures are allowed to exceed the pipe material specification limits per the "Occasional Variations Above Design Conditions" rules in ASME B31.3; $\boldsymbol{S_{hta}} \le \mathbf{1.33} * \boldsymbol{S}$ per ASME B31.3 Para. 302.2.4.(f).

- a. Very Short-Term Pressure – Limits are based on Tensile Stress (pressure spikes moving through the pipe and only exposing a particular location to the pressure for an HTA time step or a small fraction of a second).
    - i. **If a 100% CSM (2:1 CSF) and lower is required**; a 125% Safety Margin is provided by ASME B31.3 with the $1.33S$ Occasional Variation rules, so no additional modifications to pressure are required by the HTA Engineer ($S_{hta} \le 1.33 * S \le \frac{4}{3} * \frac{1}{3} S_{ut} \le \frac{4}{9} S_{ut} \le \frac{1}{2.25} S_{ut}$).
- b. Longer-term Pressure – Limits are based on Yield Stress
    - i. **If a 25% CSM (1.25:1 CSF) is required**; only a 12.5% Safety Margin is provided by B31.3 with the $1.33S$ Occasional Variation rules so they may not be used ($S_{hta} \le 1.33 * S \le \frac{4}{3} * \frac{2}{3} S_{yt} \le \frac{1}{1.125} S_{yt}$).
    - ii. A 25% Safety Margin (SM) or 1.25:1 Safety Factor (SF) is provided by ASME B31.3 with the $1.2 * S$ Occasional Variation rules so they may be used. Compare calculated pressures to 120% of the pipe material specification limits; alternately the same results are obtained by multiplying calculated pressures by 83% and comparing the resultant with unmodified pipe material specification limits ($S_{hta} \le 1.2 * S \le \frac{6}{5} * \frac{2}{3} S_{yt} \le \frac{4}{5} S_{yt} \le \frac{1}{1.25} * S_{yt}$).

3.3 In all cases, the rules above provide enough margin to account for a 21% uncertainty in the calculation. Determination of appropriate HTA uncertainty for particular applications is left to the user. For example, using the **Small** SF or SM in Item 3.2.b.ii above: a pipe that yields due to 100 psi (690 kPa) of internal pressure is never allowed more than an 80 psi (552 kPa) calculated pressure by the rules above. With a 21% or 17 psi (117 kPa) calculation uncertainty, the actual pressure might be as high as 97 psi (669 kPa) which is still less than yield. The **Small** safety factor can only be applied when there is no cavitation affecting the program results.

3.4 The HTA Engineer must always multiply HTA Forces (HTF) by an appropriate safety factor (see Stewart, Walters and Wunderlich [8]).

4.0 GENERAL GUIDELINES

The cavitation acceptance criteria are based on basic checking techniques described here in order of their significance.

4.1 Obtaining similar predictions from two mathematically different models of cavitation (DGCM and DVCM) is the strongest single indication of reliable results.

4.2 The similarity between cavitation model predictions with more than one pipe sectioning approach strengthens the reliability.

4.3 Showing that model predictions are stable with minor changes to system properties and model inputs (see Definitions for Sensitivity Checks) further improves confidence in the predictions.

Passing Check 4.1 is an indication of usable results with some margin of error to account for. Additional positive results from Checks 4.2 and 4.3 increases confidence in the results and allows the use of less error margin (i.e., lower safety factors). Conflicting results from Checks 4.2 and 4.3 reduce confidence in higher level checks but do not override them.

If DGCM vs. DVCM predictions do not agree, then predictions of the more reliable model should take precedence. The DGCM model is considered the more reliable model of the two in the absence of other indicators.

If there is uncertainty as to what safety factor to use, consider using **Large** safety factors when cavitation is more extensive, and **Moderate** safety factors when cavitation is more localized (see Definitions).

These criteria are for use with HTA based on optimized sectioning – only output from scenarios with optimized sectioning should be used as a basis for piping mechanical design. Selection of criteria for **Limited**, **Major**, and **Extreme** cavitation is based on a duplicate scenario run with the minimum acceptable number of pipe sections. The Cavitation Acceptance Criteria (CAC) is then applied to the original scenarios with optimized sectioning (see Definitions).

All criteria are based on the premise that the results do not include persistent cavitation or numerical model noise (see Definitions). Verify that cavities do eventually collapse, and the system repressurizes before continuing (the cavitation is not persistent).

These guidelines involve comparing results which are specific to a certain time frame. Where results based on different cavitation models, fluid properties, or sectioning are comparable for a given time frame, then the results of these criteria apply to that time frame. For instance, if two models show a close comparison of pressure spike magnitude and timing for the first ten seconds, but then results start to diverge, the criteria for good agreement would apply for the first ten seconds, and criteria for poor agreement would apply after that time. To compare results from different scenarios, the analyst must at least compare max/min HGL or pressure plots vs. pipe length (profile plots also known as envelope plots) and pressure/vapor volume vs. time plots (also known as history plots) of these parameters for both scenarios. Max/min HGL or pressure vs. pipe length envelope plots should cover all pipe segments and pressure/vapor volume vs. time history plots should be reviewed for key segments.

The reason for using max/min envelope plots is that it helps identify computing locations where it is advisable to generate a specific time history plot. If available in the HTA software being used, animation of HGL over time can further enhance and speed this process. Comparison of pressure spike timing and magnitude for establishing accuracy of results is most accurately done by comparing pressure/vapor volume vs. time plots.

Engineering judgment is often required to delineate the scenario comparisons. Consultation with the SME is advised when clarity is lacking.

5.0 SPECIFIC GUIDELINES

These guidelines provide direction on the application of safety factors when using pipe material specification pressure limits as acceptance criteria for pressure. When applying occasional variation rules, very short-term pressures up to 1.33 times the pipe specification pressure limits are allowed with **Small**, **Moderate** or **Large** safety factors. When applying occasional variation rules, longer-term pressures up to 1.2 times the pipe specification pressure limits are allowed with a **Small** safety factor. Use of occasional variation rules with longer-term pressures and cavitation which always requires **Moderate** or **Large** safety factors is not allowed.

5.1 Cavitation Does Not Exist

a. Criteria:
  i. Transient pressures never reach vapor pressure anywhere in the model.

b. Recommended Actions:
  i. A **Small** safety factor (1.25:1 SF) is required, however, this is already provided for by the pressure limits of the piping material specification.

5.2 Cavitation Exists in the Model, but it Occurs in Part of the System Isolated by a Closed Valve or Equivalent

a. Criteria:
  i. Transient pressures never reach vapor pressure in a hydraulically isolated (e.g., valved off) part of the system.
  ii. Transient pressures do reach vapor pressure in a remote part of the system, but only after the isolation is completed (e.g., valve completely closed).

b. Recommended Actions:
  i. For part of the system not experiencing cavitation, go to Step 5.1.
  ii. For part of the system experiencing cavitation, go to Steps 5.3 to 5.6 below, as applicable.

5.3 Limited Cavitation Exists

a. Criteria:
  i. Cavitation volumes are all below 10% of computing volume (i.e., **Limited**, see Definitions for CVR).
  ii. Important pressure spikes last for numerous computational time steps.

b. Recommended Actions:
  i. Run DVCM and DGCM scenarios
  ii. Compare results
  iii. Ignore pressure spikes of very short duration (see Numerical Model Noise) that are not reproducible when sensitivity checks are made on the model. These are not worst-case spikes because they are not real so ignore them for any considerations below.
  iv. Focus on pressure spikes that have a duration, magnitude, and timing that are reproducible when sensitivity checks are made on the model.
  v. Do results have similar/consistent results (see Definitions)?
    1. Yes
      a. Agreement of different vapor cavity model results is a strong indication of model reliability. Are peak predicted pressures within the pipe material specification limits?
        i. Yes – Use the results and conclude the sensitivity analysis. A **Moderate** safety factor (1.5:1 CSF) is required; however, this is already provided for by the pressure limits of the piping material specification.
        ii. No – Attempt to increase model confidence before proceeding with abatement due to cavitation results alone. Increase pipe sectioning and repeat DGCM and DVCM comparison. Do results still have reasonable agreement (similar magnitudes, timing, and duration of pressure spikes)?
          a. Yes – This check provides increased confidence in the results. Consider increasing system pressure rating or apply abatement to reduce pressure to within pipe material specification limits. When increasing system pressure a **Moderate** safety factor (1.5:1 CSF) is required; however, this is already provided for by the pressure limits of the piping material specification.
          b. No – Consider further model sensitivity checks and repeat comparisons to see if it provides more consistency. Did additional checks provide more agreement between the two cavitation models?

        i. Yes – Consider increasing system pressure rating or apply abatement to reduce to within pipe material specification limits based on the most consistent results found so far. When increasing system pressure, a **Moderate** safety factor (1.5:1 CSF) is required; however, this is already provided for by the pressure limits of the piping material specification.
        ii. No – The original, consistent results still have credibility. Consider applying abatement or increasing the system pressure rating. When increasing the system pressure rating, a **Large** safety factor (2:1 CSF) is required. When using a **Large** safety factor, very short-term pressures must be less than the pipe material specification limits. Longer-term pressures must be less than 75% of the pipe material specification limits.

2. No
    a. Increase pipe sectioning and repeat DGCM and DVCM comparison.
    b. Does one cavitation model tend to produce consistent pressure and vapor volumes when pipe sectioning is increased?
        i. Yes
            1. Focus on results from the cavitation model with consistent results and ignore other cavitation models as unreliable.
            2. Apply a **Large** safety factor (2:1 CSF): When using a **Large** safety factor, very short-term pressures must be less than the pipe material specification limits. Longer-term pressures must be less than 75% of the pipe material specification limits. If the pressure is within these acceptable limits, then no further action is required. If the pressure is not within these acceptable limits, then apply abatement or increase the system pressure rating.
        ii. No
            1. Options
                a. Contact the HTA software vendor so they can assess whether there is a weakness or problem with one of the cavitation models in this situation and perhaps provide insight or a workaround.
                b. In consultation with the SME, consider turning cavitation modeling off altogether (allowing pressures to go below vapor pressure and potentially below absolute zero) and see if peak pressure spikes give any insight into the peak pressure magnitude and timing. Use this as another data point in assessing the credibility of the cavitation model's pressure spike predictions.
                c. Conclude that cavitation results are not reliable and consider applying abatement that changes cavitation results. Consider modeling the system in alternative software.

5.4 Major Cavitation Exists

a. Criteria:
    i. Some cavitation volumes are above 10% of computing volume, but none are above 100% (i.e., **Major**, see Definitions for CVR).
    ii. Important cavitation spikes last for numerous computational time steps, so they are not attributable to numerical model noise.
b. Recommended Actions:
    i. Follow the Step 5.3, except always use a **Large** safety factor (2:1 CSF) instead of **Moderate** safety factor. When using a **Large** safety factor, very short-term pressures must be less than the pipe material specification limits. Longer-term pressures must be less than 75% of the pipe material specification limits.

5.5 Extreme Cavitation Exists

a. Criteria:
    i. Some cavitation volumes are above 100% of computing volume (i.e., **Extreme**, see Definitions for CVR).
b. Recommended Actions:
    i. Resection model (using both fewer and more sections) and rerun.
    ii. Does **Extreme** cavitation still exist?
        1. No
            a. Give more credibility to scenarios where **Extreme** cavitation does not exist.
            b. Use Steps 5.3 or 5.4.
        2. Yes
            a. The best available analysis is unable to conclude that this scenario is safe. Apply transient abatement to reduce cavitation to **Major** at worst and go to Step 5.3 or 5.4.
            b. Consider modeling the system in alternative software.

5.6 Persistent Cavitation Exists

a. Criteria:
   i. Regardless of cavitation volume sizes, some parts of the system drop to vapor pressure and never decisively rise above vapor pressure (see Persistent Cavitation).
   ii. This behavior is not transient cavitation but true two-phase flow.
b. Recommended Actions:
   i. The best available analysis is unable to conclude that this scenario is safe. Apply transient abatement to reduce cavitation to an acceptable level and conclude analysis.
   ii. Consider modeling the system in alternative software.

This concludes the guideline. See Discussion section below for background information on the guideline.

DISCUSSION

The Collaboration Process, Resources, and References Used

These criteria began with high-level design guidelines as summarized in Chaudhry [5]. Emerging guidelines for hydropower fluid transients exist but, due to the nature of the application and hydropower industry experience, highly recommend avoiding transient cavitation altogether (Pejovic and Karney [9], Pejovic et al. [10], Bergant et al. [11]). Discussions of risk management for fluid transients are available (Anderson [12], Thorley [13]). These are useful starting points.

The authors noticed that the safety factors recommended by Chaudhry [5] coincide in many cases with the safety factors provided by following the code requirements in ASME B31.3 Piping Code [1]. The 3:1 safety factor against burst recommended for normal operations in [5] matches the 3:1 safety factors required for normal operations by [1]. For common materials where 0.89 times yield strength (1.33 times 2/3 yield) is less than half of the tensile strength of the material, the occasional variation rules in [1] match the 2:1 safety factor against burst for low probability events recommended by [5]. It was also noticed that, for longer-term pressures, the failure mechanism of pipe burst can occur due to hoop stress at or above the yield strength of the material. In these cases 3:1, or even 2:1 factors of safety are not provided merely by keeping calculated presure within the piping code limits [1]. More detailed consideration was required and was provided by the authors based on experience with the ASME B31.3 Piping Code [1].

The developers of the HTA software used in this project are aware of the limitations of the DVCM and DGCM models through the literature (Wylie and Streeter [4], Bergant et al. [6]). However, even more importantly, they are aware through sometimes arduous personal experience over more than two decades of development, training and technical support provided to a broad range of industries and applications.

The extensive discussions and collaboration over many months allowed the experience of the HTA software developers to be translated into safety factors relevant to this paper's authors and Pipe Stress Engineers in general.

Calculation Uncertainty Without Cavitation

While HTA results without cavitation can be validated much more readily than those with cavitation, and are expected to be reliable, like all calculations, they do include some uncertainty. Where steady-state fluid velocity is calculated, error in this calculation also contributes directly to HTA calculation uncertainty. Pipe dimensional tolerances, variation in pipe roughness, uncertainty in major and minor hydraulic loss values and fluid properties all contribute to uncertainty in the fluid velocity.

Another uncertainty mentioned earlier in this paper is the uncertainty that results from pipe sectioning round-off errors. This is a standard aspect of MOC (Applied Flow Technology [2], Wylie and Streeter [4], Chaudhry [5]) and the conventional discussion notes that wavespeed is the most uncertain parameter that affects pipe sectioning. As a result, sectioning round-off errors of ±15% are suggested as acceptable [4]. The authors of this paper prefer to limit this to ±10% whenever possible. Hence the "Optimized Sectioning" in Guideline section 2.0.

Uncertainty of up to 25% in non-cavitating models are accounted for in these criteria as it applies to safety factors.

Some Noteworthy Items on the DVCM and DGCM

When transient cavitation occurs, vapor forms in the pipe. The existence of vapor can significantly change the fluid acoustic velocity and, hence, wavespeed as discussed in Wylie and Streeter [4], Chaudhry [5] and Bergant et al. [6]. Typical MOC software such as Applied Flow Technology [2] assumes the wavespeed is constant over time. This is one of many uncertainties introduced in transient cavitation modeling.

The DVCM is a purely mechanical model of cavitation which makes no attempt to capture any thermodynamic or gas physics behavior. The DGCM, on the other hand, includes a gas equation of state and thus makes some attempt to capture the gas physics (Wylie and Streeter [4], Bergant et al. [6]).

The DVCM is simple to understand and implement in software. References [4-6] discuss the methodology for DVCM for internal pipe computing sections. Extending the DVCM to typical pipe system boundary conditions (e.g., valves, tees) is discussed elsewhere by Walters [14]. It is fairly straightforward and typically involves simple, closed-form solutions.

The DGCM, on the other hand, is much more complicated to implement in software especially as it relates to typical pipe system boundary conditions. To the authors' knowledge the literature does not discuss how to extend the DGCM to typical pipe system boundary conditions (e.g., valves, tees). Textbook discussions (e.g., Wylie and Streeter [4]) often assume an instant or rapid valve closure at the end of a pipe.

Lacking published methods means that software implementations are more susceptible not only to programming errors (because of the complexity of the method) but to errors in fundamental methodology for each boundary condition implemented. The mathematics needed to solve each boundary condition are more complicated, not closed-form, and almost always require significant iteration of multiple simultaneous equations. To emphasize this point, the second author of this paper attempted to develop an analytical expression for the DGCM across an open valve with upstream and downstream piping. It resulted in a 16th order polynomial which meant 16 roots. Neither Mathcad nor Mathematica were able to solve for the roots analytically. In contrast, the DVCM across a valve can be represented as a 2nd order polynomial (Walters [14]).

Making the situation worse, published validation cases and/or data are lacking for systems with valves, tees and other typical pipe system boundary conditions. Thus, there is nothing against which to check the software implementation of the DGCM.

When data is available (typically for simple, single pipe systems), it typically shows that:

- the DGCM is more accurate than the DVCM
- the DGCM is less susceptible to numerical model noise (see Guideline section 2.0)
- the DGCM is better at predicting the timing of pressure spikes

The final bullet point is explained in Liou [15] which discusses how the DGCM has mathematical properties which allow it to approximate the variable wavespeed that occurs once vapor is generated.

One significant drawback of the DGCM compared to the DVCM is that the DGCM always assumes a free gas volume exists at each computing section (even when the operating pressure is well above vapor pressure). This means that MOC software runtimes are significantly longer for non-cavitating simulations with DGCM than DVCM. Hence Guideline section 2.0 on DGCM vs. DVCM.

Interpreting HTA Cavitation Predictions

Techniques and strategies for assessing the reliability of predictions generated by the DVCM and DCGM have been developed by the HTA software authors over many years. Guideline section 4.0 discusses these.

Numerical model noise (Guideline section 2.0) is inherent in the DVCM and DGCM models. The most important aspect of interpreting cavitation predictions is determining what is numerical model noise and what is not. Real, physical pressure spikes tend to last for numerous time steps in the simulation. They have “breadth” or “duration”. Numerical model noise tends to last for one time step or a few time steps at most. Thus, HTA Engineers should look for pressure spikes that have breadth or duration. Those that do not are typically numerical model noise that can be disregarded as not real.

In the HTA software authors’ opinion, generating similar results from DVCM and DGCM models is the strongest indication of a reliable prediction. The two models use different mathematics with different physics to simulate the formation and collapse of cavities. When the predictions from both models agree with each other, that is significant and a strong indicator that transient cavitation is being modeled reliably.

Other techniques and strategies involve using sensitivity checks (Guideline section 2.0). The basic idea is that a real, physical pressure spike will retain its magnitude, timing and duration (within some tolerance) when small changes are made to the model. For example, if more sections are added to a model and a pressure spike disappears, then it is doubtful that the pressure spike is real.

Other types of sensitivity checks involve making small perturbations (say 0.1-1%) to liquid density, vapor pressure, boundary condition values (e.g. valve Cv), etc. The rationale is that small perturbations in the model input values should result in small changes to the output. Simpson and Bergant [16] use a similar technique with regard to pipe sectioning and model perturbations.

It is well known in the HTA community that a finer mesh (smaller pipe sections and time step) does not affect the accuracy of MOC predictions. This is inherent to how MOC works. However, when transient cavitation occurs, MOC predictions can and do change with sectioning. Simpson and Bergant [16] discuss that the DGCM model may show increased accuracy with a finer mesh. The DVCM model does not. Whichever cavitation model is used, pipe sectioning changes should not result in significantly different predictions when the pressure spikes are real.

For completeness, it is worth mentioning another completely different approach to interpreting HTA cavitation results by McGuffie and Porter [17] and McGuffie [18]. In this approach, a numerical filter is used to distinguish between numerical model noise and physical transients. Note that the study used the same software as the present authors (Applied Flow Technology [2]) albeit an older version available in 2007. At least in some cases, they appear to be dealing with persistent cavitation (see Definitions section 2.0). As noted in the Guideline section 5.6, persistent cavitation is not addressed in this paper.

Severity of Cavitation

References on transient cavitation (Wylie and Streeter [4], Bergant et al. [6]) note that the volume of vapor can grow large with respect to the size of the computing volumes. In order to offer some pragmatic guidance, the references suggest that the cavitation models lose accuracy when the volume of vapor is greater than 10% of the computing volume. This is the **CVR_{MAX}** value discussed in Guideline section 2.0.

The HTA software authors have found that the DVCM and DGCM can, in some cases, still offer useful and relatively reliable predictions when the **CVR_{MAX}** is greater than 10%. When this is the case, it is more likely when **CVR_{MAX}** > 10% occurs at one location in the system (see Definitions section 2.0 on Localized vs. Extensive Cavitation).

Kamemura et al. [19] offer experimental results which Applied Flow Technology [2] can match relatively well even though the **CVR_{MAX}** is predicted to be significantly greater than 10% (it is roughly 50% in one area of the system and 15% in another). The HTA software authors of this paper are thus reluctant to disregard all results when $\mathbf{CVR_{MAX}}$ > 10% as suggested in Wylie and Streeter [4]. However, the authors felt it important to recognize that the predictions may very well be less reliable when $\mathbf{CVR_{MAX}}$ > 10%. Therefore, a decision was made to use the results but also to recommend a larger safety factor (see Guideline section 5.4) because of the greater uncertainty.

When the vapor volume grows larger than the computing volume ($\mathbf{CVR_{MAX}}$ > 100%) it is clear the physical model has been pushed beyond reasonable use. The MOC is just not designed to handle transients when entire computing sections of liquid are vaporized. It was therefore decided to conclude all such results are unreliable (Guideline section 5.5).

It is important to note that changing the pipe sectioning will change the $\mathbf{CVR_{MAX}}$ value. As a rule of thumb, decreasing the pipe section length by 50% (i.e., doubling the number of pipe computing sections) also doubles the value of $\mathbf{CVR_{MAX}}$ should the absolute vapor volume prediction remain unchanged. The reason is that more computing sections do not necessarily reduce the amount of absolute vapor generated. Hence the ratio of vapor volume to computing volume (CVR) tends to increase when the computing volume is decreased. For this reason, Guideline section 2.0 (under Sectioning) recommends evaluating the severity of cavitation with the minimum number of computing sections possible.

An example of this can be found in Walters and Leishear [20], Example 2. Doubling the number of computing sections in the simulation from 12 to 24 increases the $\mathbf{CVR_{MAX}}$ value from 0.27% (as shown in [20]) to 0.46% (independent check by the second author of this paper).

Use of Software Animation Features

While it is not a part of this proposed guideline, utilizing animation features of the predictions in HTA software can be a critical element in understanding transient cavitation (Locher et al. [21]). This capability is available in the HTA software used for this project [2]. HTA Engineers are strongly encouraged to use animation whenever possible.

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