Mechanical Response of Shells to Tube Rupture in STHEs

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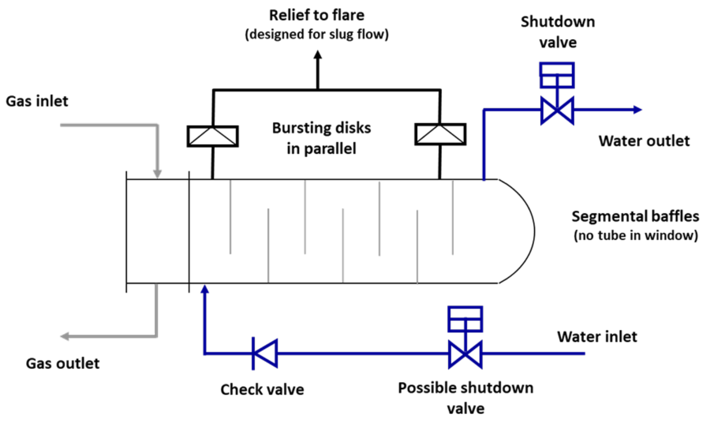
Talk outline

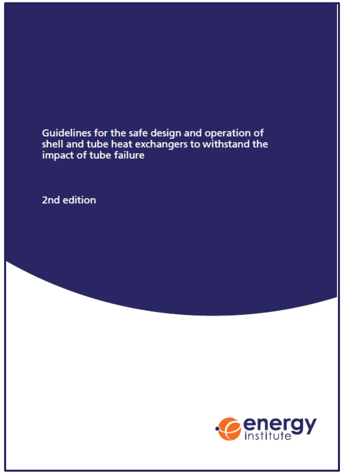
- Context and Background
- Surge caused by tube rupture
- Shell response
- Effective pressure
- FE Validation
- Guidelines on relief device design

Background

- 2nd revision of design guidelines on the effects of tube rupture published by the Energy Institute.
- Guidance provided on relief devices and system protecting the STHE from mechanical damage.
- Assumes shell stresses determined from a conventional static analysis.
- Concern that there may be shell vibration, to a level which may damage or fail the shell wall.



Adapted from IP Guidelines for the Design and Sae Operation of Shell & Tube Heat Exchangers to Withstand the Impact of Tube Failure, Aug 2000

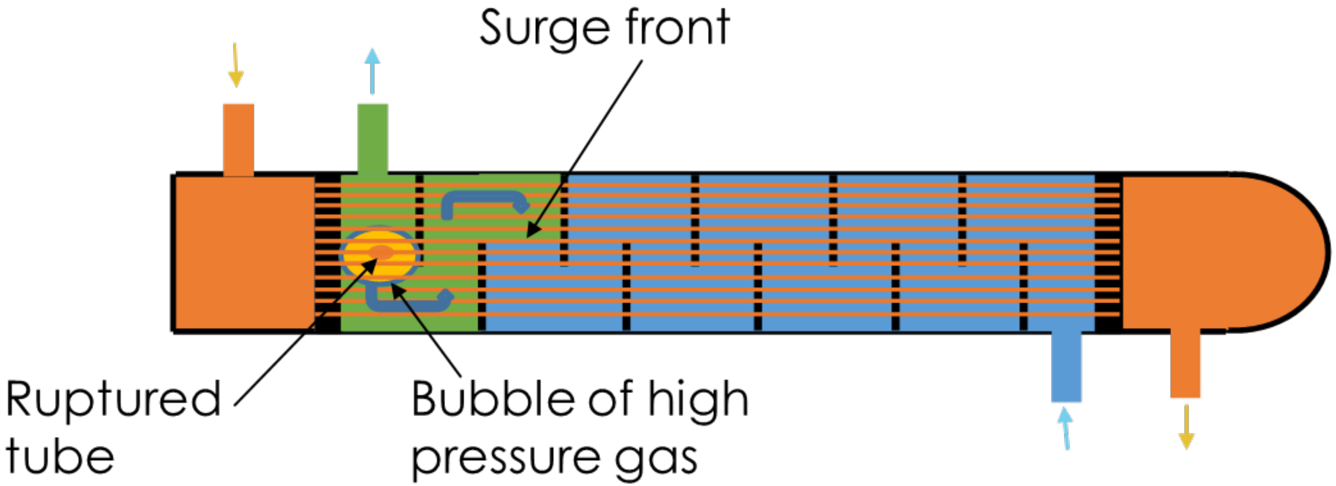


Baseline review

- Review of experience and methods used to determine the effects of tube failures
- Predominant mode of tube failure is leak-before–break.
- Circumstances of fully circ. tube rupture or longitudinal splitting may occur.
- Hydraulic analysis used to determine the pressure pulse from a tube rupture.
- Shell stress magnification caused by the dynamic effects of the pressure pulse
- Companies recognise the threat to shell integrity from dynamic effects but do not normally do dynamic structural analysis.
- Mitigation of the risk is provided by the pressure relief system, periodic in-service inspection of the tubes, and leak monitoring.

Process

Pressure step at surge front P_{is}



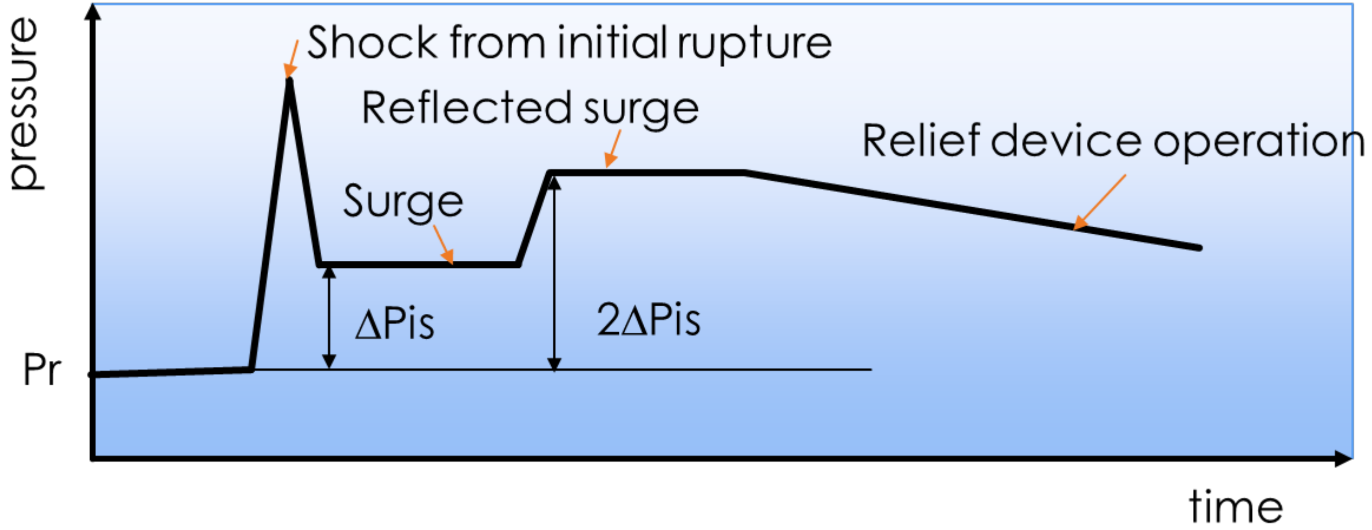
Calculation of surge pressure step

EI Guidelines for the safe design and operation of shell and tube heat exchangers to withstand the effects of tube rupture gives the step pressure as:

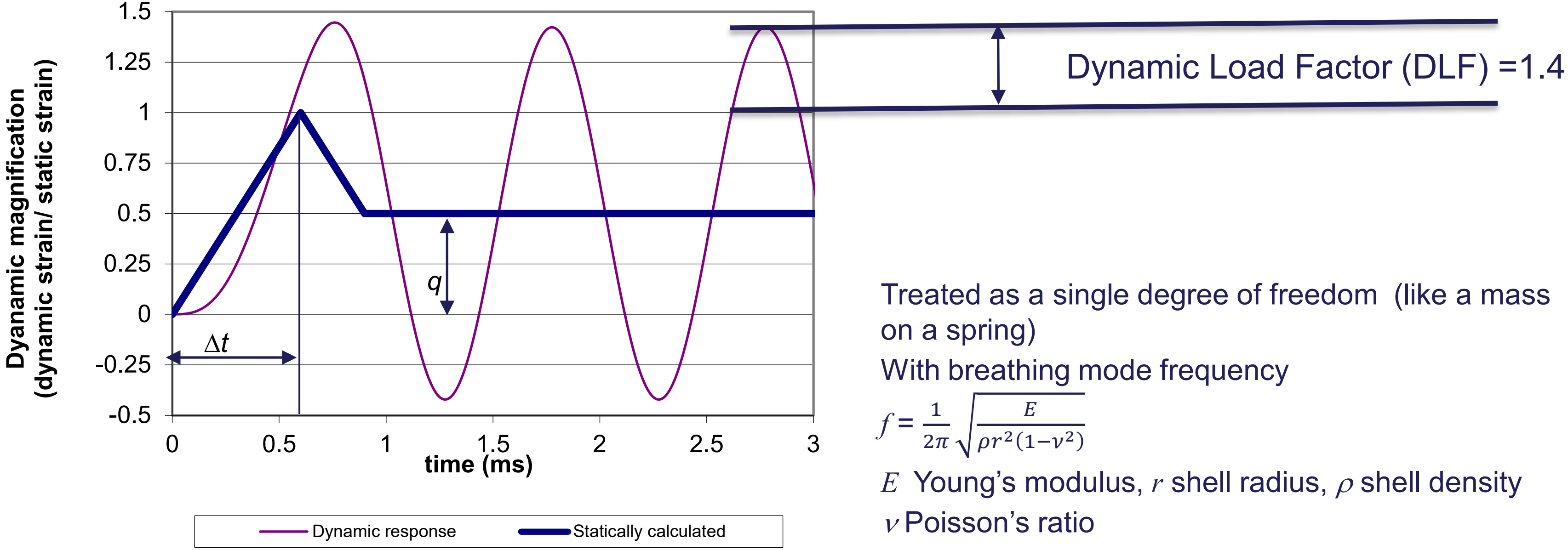
$$P_{is}(P_{is} - P_r)^{\gamma} = \left(\frac{2}{\gamma + 1}\right)^{\gamma/\gamma - 1} P_0 \left(\frac{C_D a \rho_l c A_t}{A_s}\right)^{\gamma}$$

γ	Ratio of specific heats	P_r	Shell pressure (Pa)	P_0	Tube pressure (Pa)
C_D	Tube discharge coeff. (0.62)	a	Speed of sound in gas (m/s)	ρ_l	Liquid density (kg/m^3)
c	Speed of sound in liquid (m/s)	A_t	*2 x* ruptured tube area (m^2)	A_s	Characteristic flow area (m^2)

Pressure at any point on shell



Shell response



Treated as a single degree of freedom (like a mass on a spring)

With breathing mode frequency

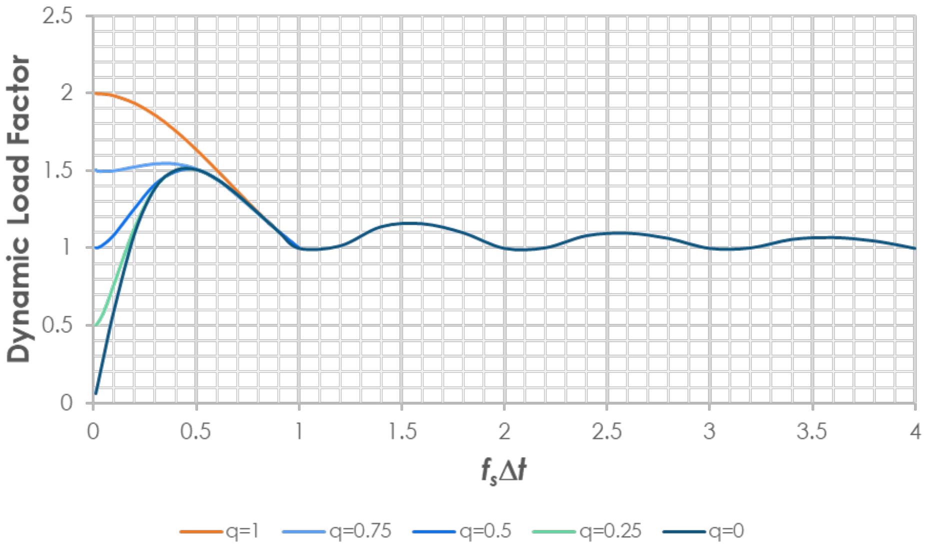
$$f = \frac{1}{2\pi}\sqrt{\frac{E}{\rho r^2(1-\nu^2)}}$$

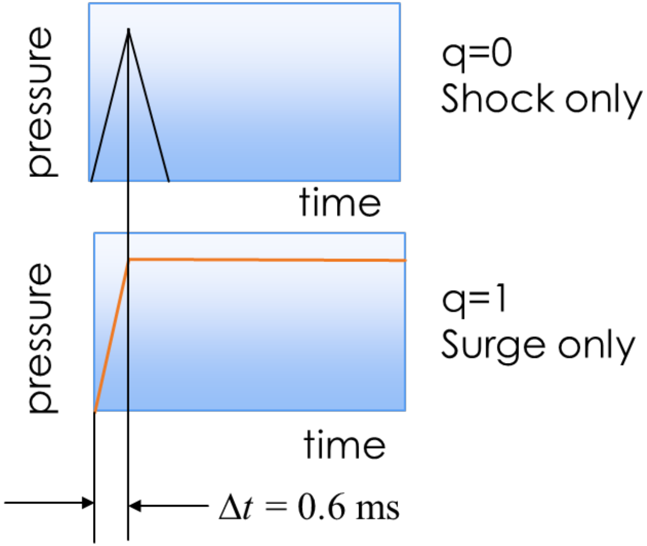
E Young's modulus, r shell radius, ρ shell density

ν Poisson's ratio

Effective pressure

- **'Effective pressure'** = Static pressure giving the same stresses on shell as vibration = Pressure (eg Pis) x DLF + Pr





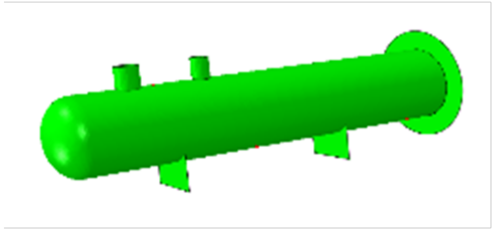
Validation of Approach using FEA

- Evaluation of the surge pressure variation with time, which is key to how the shell will respond. Two types of information are available:
  - Tests carried out by the Health and Safety Laboratory (HSL) on an instrumented STHE.
  - One-dimensional flow calculations by Hydraulic Analysis Ltd (HAL) on three typical STHEs of various sizes.

- Finite element (FE) models of the HSL test STHE were constructed. These were used to confirm that FE modelling could predict the strains measured with strain gauges on the test with reasonable accuracy.

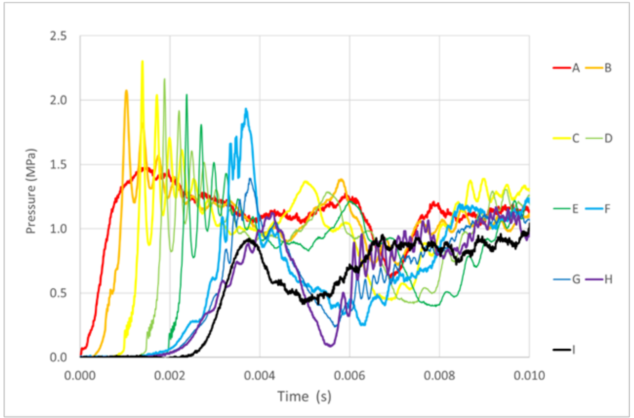
- Further FE of the vessels analysed by HAL, representative of actual vessels, were then developed.
  - Used to determine the full range of natural frequencies and their spectral response.
  - Also determined the variation of stress in the shell wall with time and hence the DMF.

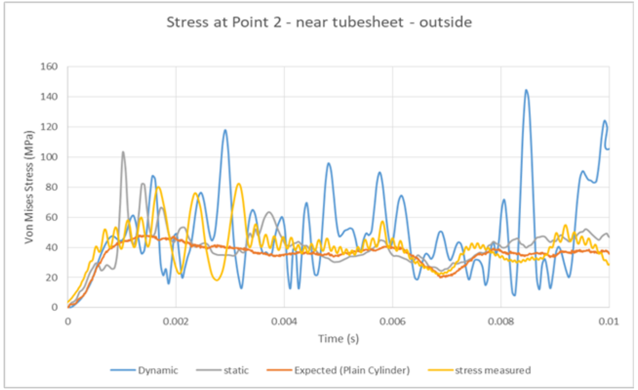
Validation of Approach using FEA



HSL Test Idealisation

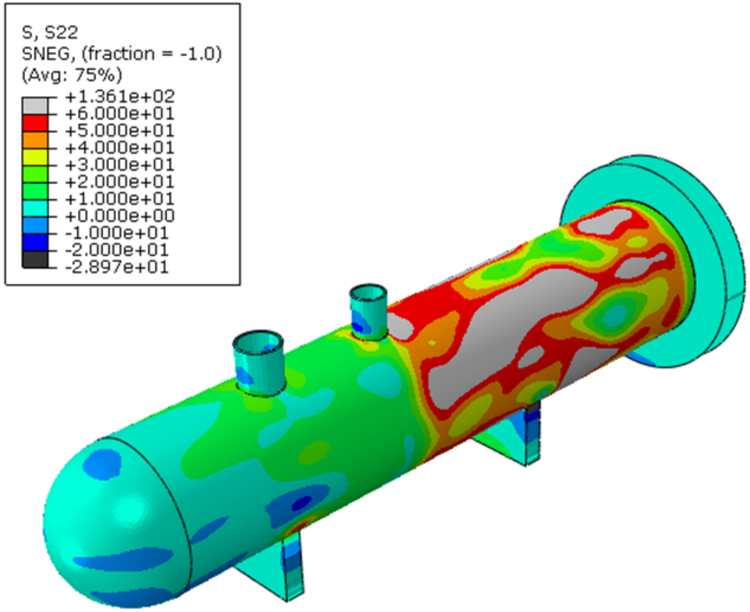
Pressure Transient (from Measurements)

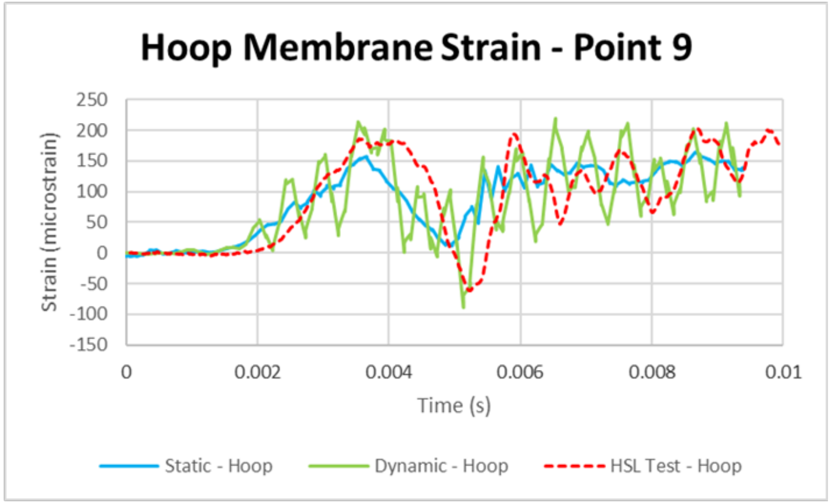




Predicted and Measured Response

Validation of Approach using FEA





Validation of Approach using FEA

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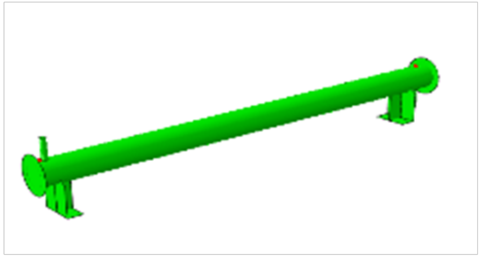

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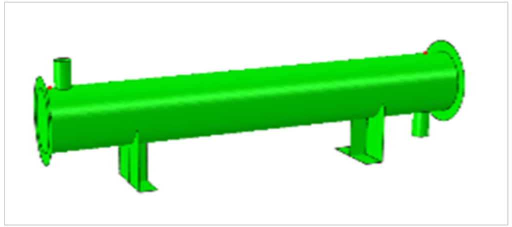

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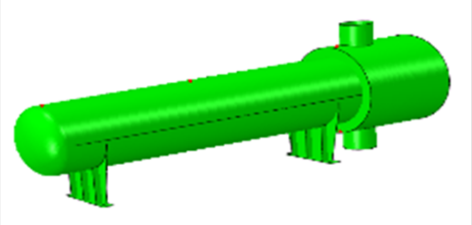

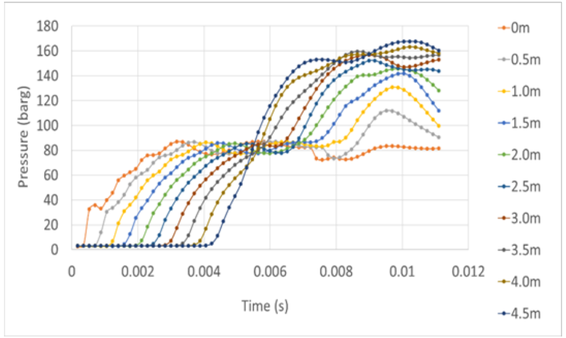

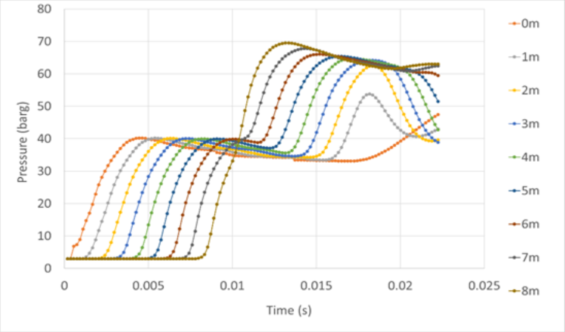

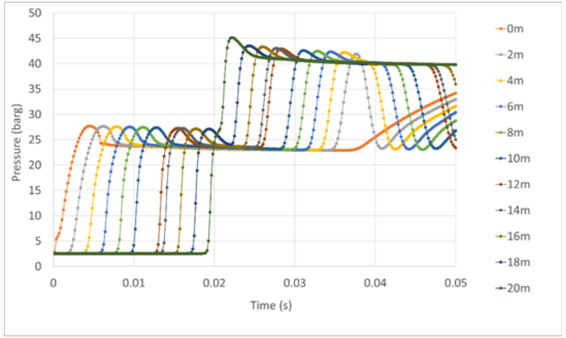

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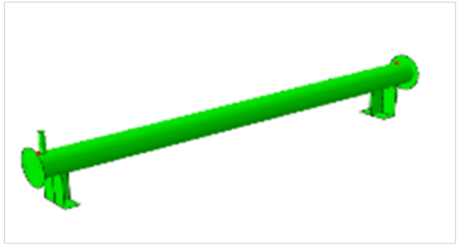

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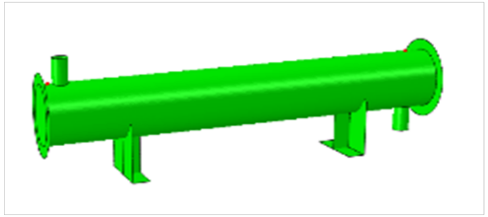

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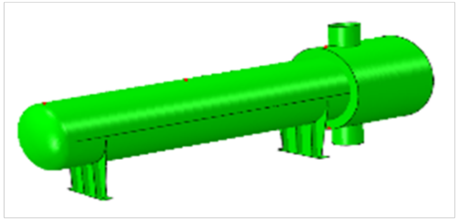

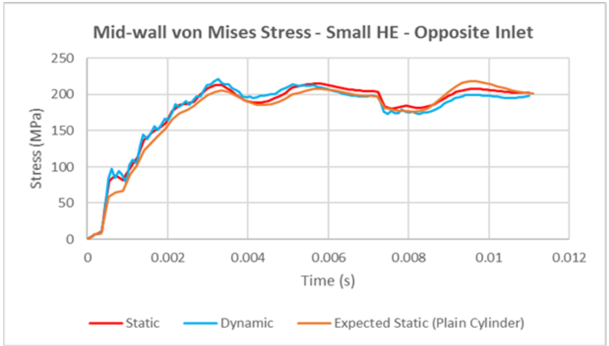

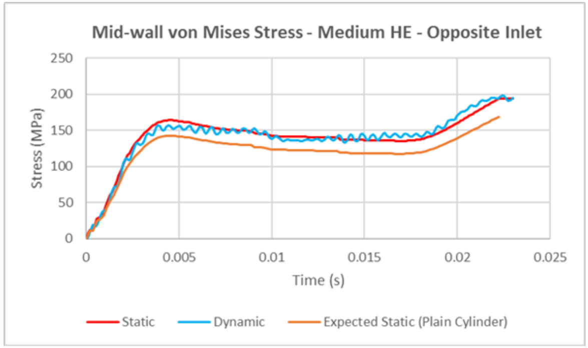

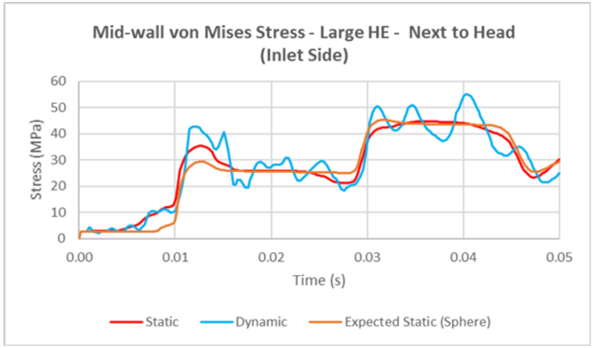

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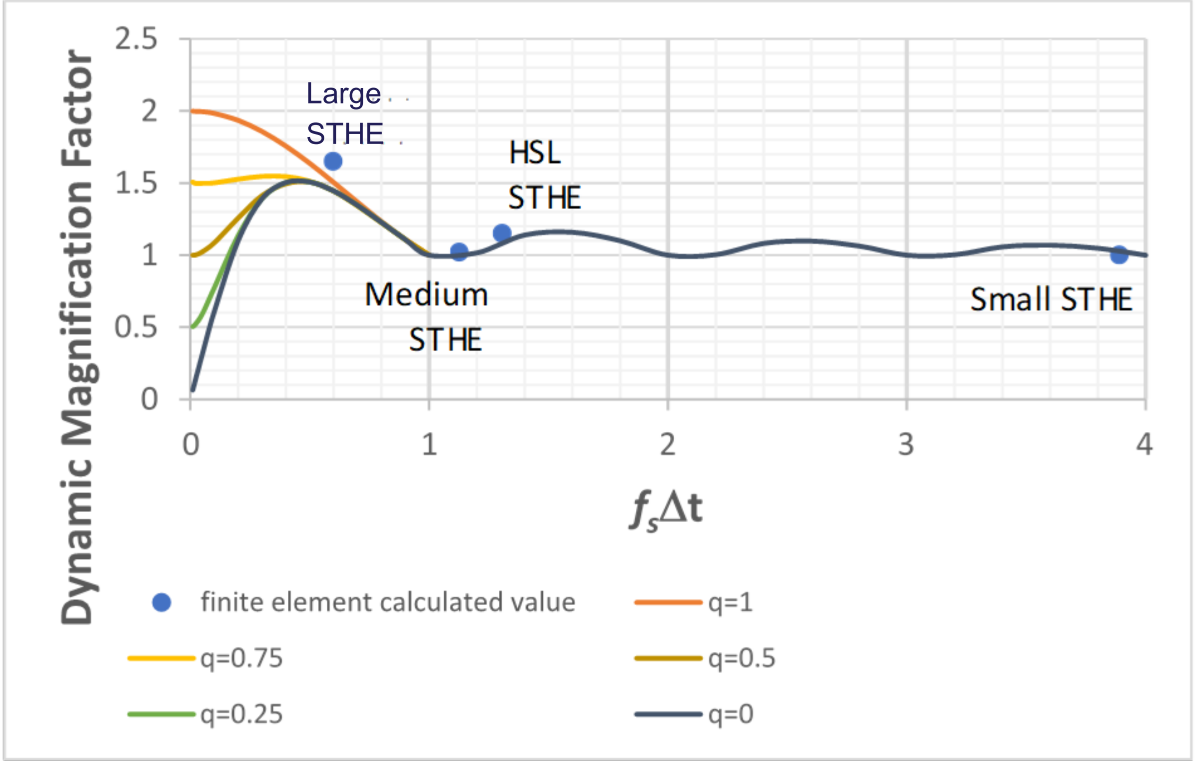
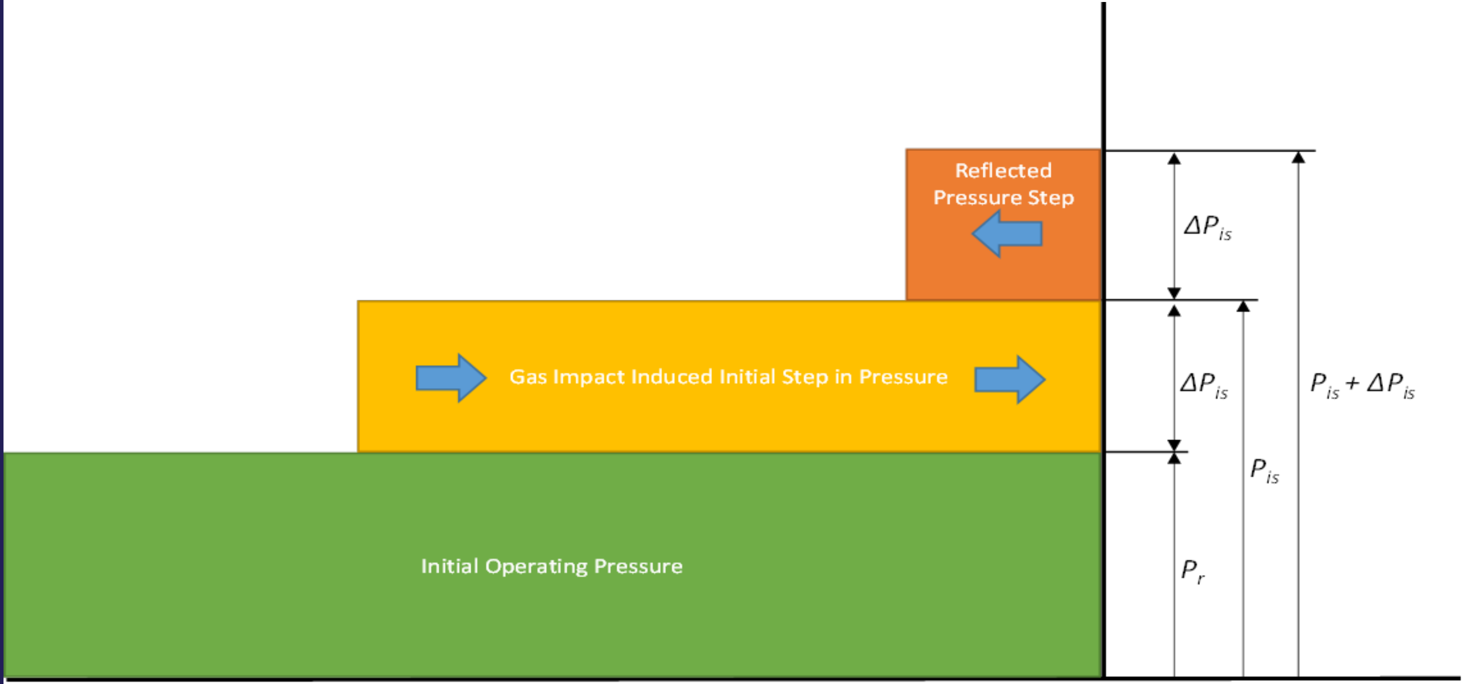


Conclusions from the stress analysis

- Statically calculated surge stresses can be approximated by simple pressurised cylinder equations.
- Dynamic enhancement to the static stress caused by shell wall oscillating as the surge passes appears to be associated only with the breathing mode.
- Small and medium sized STHEs with radii in the range of typically 100mm to 500mm have insignificant dynamic magnification of the statically determined stresses.
- For larger heat exchangers, dynamic magnification of stresses is more significant.
- The duration of dynamic oscillations, is limited to a few cycles because of the damping of the fluid in the shell.
- Should the tube fail close to the shell there is the possibility of impulsive full tube pressure pulse impacting the wall which may result in high localised stresses.

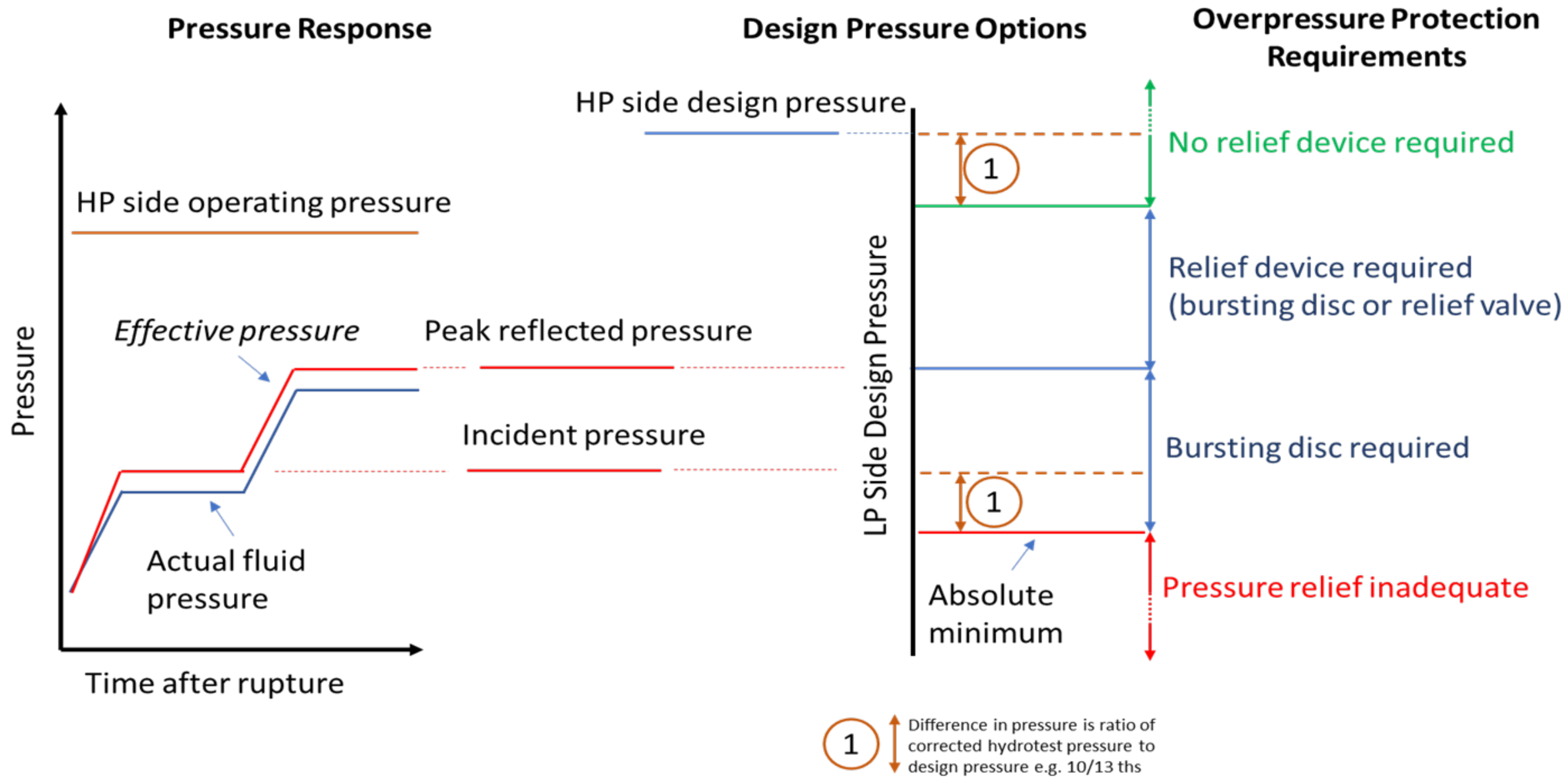
Schematic of impulse step pressure



Changes to current method

- The current methodology can be modified to take account of the possibility of structural resonance due to the dynamic magnification by applying a dynamic load factor (DLF) to the surge pressure.
- This establishes an effective pressure which approximates the stress experienced by the shell in excess of the stress due to fluid pressure.
- The effective pressure has implications for the options for setting the design pressure of the shell and the corresponding overpressure protection requirements for tube rupture.

Integrating design guidance with mechanical response



Simplified and conservative rules

$f_s \Delta t_{min} < 0.8$	Use single degree of freedom model as DLF > 1.2
$0.8 < f_s \Delta t_{min} < 1.8$	DLF = 1.2
$1.8 < f_s \Delta t_{min}$	DLF = 1.1

Overall conclusions

- Under certain conditions there can be dynamic enhancement to the static stress caused by the shell wall oscillating as the pressure surge passes.
- This dynamic magnification can be estimated using a validated single degree of freedom model based on the cylinder breathing mode.
- This simplified model can be used without the need for extensive structural modelling to determine a dynamic load factor which can be applied to the fluid surge pressures following tube rupture.
- The resultant effective pressure imposed on the shell wall during the tube rupture event can be used to inform engineering decisions concerned with determining the design pressure of the shell and its overpressure protection requirements.
- The Energy Institute Guidelines require updating to account for the mechanical response of the shell wall to ensure that heat exchangers and their overpressure protection systems are adequately designed to prevent a loss of containment in the unlikely but credible event of a tube rupture.

Thank you

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