EFFECT OF CRITICAL VOLUME AND ENCLOSURE SURFACE AREA IN A BIMETALLIC STEAM TRAP RESPONSE

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Abstract - *Steam traps are valves that are used in industries that use steam for their processes, to remove condensate generated in steam line and not letting steam out. This helps in keeping the process efficiency high and preventing steam discharge. Thermostatic bimetallic steam trap considered here works based on the principle of thermal expansion. Exposure to steam and higher temperature stimulates the sensing elements to expand close the valve. Even though the element expansion is directly defined as a parameter of temperature in all designs, the control/critical volume around the element as well as the trap external surface area plays a crucial role in the trap response. A mathematical model comprising of the effect of both the mentioned parameters on sensing element response was developed. A heat transfer CFD model was developed to find out the heat available within the control volume & heat lost through the trap body to the atmosphere to calculate whether the sensing elements receive a satisfactory amount of energy to actuate. Through this exercise, the control/critical volume around the elements and trap body was optimized for satisfactory performance.*

Key Words: Steam Trap, Bimetal, CFD, Natural Convection, Energy conservation, Heat transfer, Critical volume, Trap response.

1.INTRODUCTION

Steam traps play a major role in every industry that utilizes steam to transfer energy, in keeping the process efficiency high by discharging condensate formed from the distribution line based on process criticality. Based on application and requirements, various types of steam traps are used. A thermostatic steam trap is the traps works on the principle of temperature. Temperature acts as a driving parameter in actuating the trap mechanism. When it comes to thermostatic steam traps, there are two types, balanced pressure trap, and bimetallic steam trap. The trap of interest here is the bimetallic steam trap. The bimetallic trap uses bimetallic alloy strips as the actuator in the mechanism. Upon coming in contact with steam and saturated condensate, the bimetallic element expands which in turn actuates the valve and closes the same. The mechanism stays closed until the temperature of condensate reaches a set subcooled temperature & discharges condensate at a set temperature. This response ensures that the process utilizes the sensible heat available and prevents energy wastage and increases process efficiency.

Based on the design model for bimetal elements, the mechanism for the\bimetallic steam trap was calculated, designed, and developed. The developed mechanism was tested under a plethora of conditions initially, and the results were analysed. The results or responses obtained from the testing done and theoretical models were distinctly different. Initial probing and tests confirmed that the surface area of the mechanism enclosure and effective C_V around the mechanism had an impact on the response. Based on this inference, further study was done to find the relation between the above-mentioned parameters and the actual response of the mechanism. A natural convection heat transfer CFD model available in ANSYS-FLUENT 16.1 was used to find the heat losses and to calculate the effective energy available within the control volume for the mechanism to actuate. The results obtained from the CFD study and calculations were together used to figure out the expansion possible with the current elements. The inferences from this study were used to optimize the mechanism design to obtain a satisfactory response.

2. LITERATURE

2.1 Thermostatic Steam Trap

The thermostatic bimetallic steam trap uses the temperature of steam and condensate to operate. The bimetal alloy elements expand upon coming in contact with high-temperature steam and condensate and this expansion is converted to valve operation by closing the valve seat. The schematic of the mechanism is as shown in *Fig-1*.

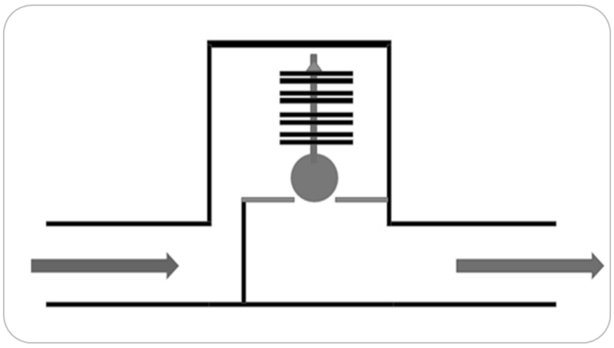

Fig -1: Bimetallic steam trap schematic

Every thermostatic steam trap is set for a specific discharge temperature known as the degree of sub-cooling (DOS). The thermostatic bimetallic steam trap holds back the steam and condensate until the temperature drops and reaches this set DOS. Once the condensate temperature drops below the set DOS, the mechanism and elements contract to open the valve seat and discharge the condensate. This setting for DOS shall be given based on the process and its criticality. This is to ensure that energy consumption from steam and the process efficiency is maximized.

In the valve mechanism, bimetal expansion forces or thermal forces (F_T) generate the valve closing force. There are two types of bimetallic steam trap mechanisms, pressure-to-close, and pressure-to-open. In the pressure-to-close configuration, the pressure adds up to the closing force and helps in closing the valve. On the other end, in pressure-to-open configurations, the pressure forces resist the closing forces generated by bimetallic elements. Compression springs are used in a few designs, usually in pressure-to-close configurations, to keep the valve open. This not only ensures the always open valve configuration but also defines from what temperature the elements start to deflect as the spring cancels out the initial forces generated by bimetal elements.

2.2 Bimetallic Element

Bimetallic element or strip converts temperature change (ΔT) into mechanical work by expanding and exerting force. These elements/strips are made of stacking two or more dissimilar alloys with different thermal expansion coefficients. Upon coming in contact with a heat source, the element expands in a controlled manner due to differential expansion of the component alloys. The higher expansion side (HES) expands more compared to the Low expansion side (LES) to generate a controlled deflection as shown in *Fig.2.*

There are various shapes of elements that are available or commonly used. The standard or commonly used shapes are

- Cantilever type element – fixed at one end
- Simply supported beam type element – supported at both ends
- U-shaped element – fixed at one end of U
- Spiral or Helix type element
- Disc type element

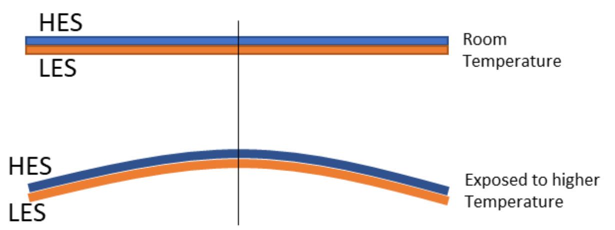

Fig -2: Bimetallic element Response

Based on the type of element, the response parameters vary. The response parameters of the element such as mechanical force generated and displacement generated are functions of temperature and geometrical dimensions of the element. For the thermostatic bimetallic steam trap considered here, the shape of the element is a cantilever. The response parameters of the cantilever element, which are a function of temperature, are as follows-

Displacement generated – $$D = \frac{a.\Delta T.L^2}{t} \quad \text{(eq.1)}$$

Equivalent Thermal Forces – $$F_t = \frac{E.a.w.t^2.\Delta T}{4.L} \quad \text{(eq.2)}$$

Mechanical Force generated – $$F_m = \frac{w.E.t^3.D}{4.L^3} \quad \text{(eq.3)}$$

Where,

a = Specific deflection of the Bimetal element.

L = Length of the cantilever element (m).

w = width of the cantilever element (m).

t = thickness of the cantilever element (m).

E = Young's modulus of the Bimetal element (N/m^2).

Equations for calculating mechanical forces are derived by substituting the displacement equation in the thermal force equation. The thermal force is equivalent to the load required to bend a cantilever beam and deflect it by δ (D). And the value of specific deflection varies for different element shapes and materials.

The bimetal element has a working or operating temperature range under which the element will not fail or damage. The element must be operated within that limit range to ensure better performance. However, the response is only linear for a smaller range which is a subset of the entire operating range. Post that, displacement increments are non-linear and have a lower increment which gradually flattens out because of the change in specific deflection (a).

The element considered for this application was selected considering the limit and linearity range to ensure better response and safety of the design.

3. DESIGN CALCULATION & CHARACTERISTICS

The bimetal elements are usually stacked in a particular fashion to maximize expansion and mechanical forces and facilitate the actuation of the valve. Design calculation was done for the mechanism, considering the bimetal element used, to define the stacking as well as the mechanism response characteristics.

The major parameter that controls the mechanism characteristics is the specific deflection constant of the bimetallic element. To identify the relation of variation between the constant and temperature, the element was tested at various temperatures, and displacements were measured. The relation between the specific deflection constant and temperature is as shown in *Chart-1*. The specific deflection is the proportionality constant of thermal expansion, D, and thermal forces, F_T generated by a bimetal element, and is inversely proportional to temperature at higher temperatures. The design calculation was done to identify the mechanism response characteristics considering this. The intended function of a bimetallic steam trap, or any thermostatic steam trap, is to discharge condensate at a specific degree of subcooling. This implies that for a given operating range, the response characteristics follow the saturation curve of steam-water. So, for a given pressure if water exists at saturation temperature, the bimetallic steam trap is to discharge condensate at a fixed lower temperature than saturation temperature; hence a response curve similar to the saturation curve with a fixed offset.

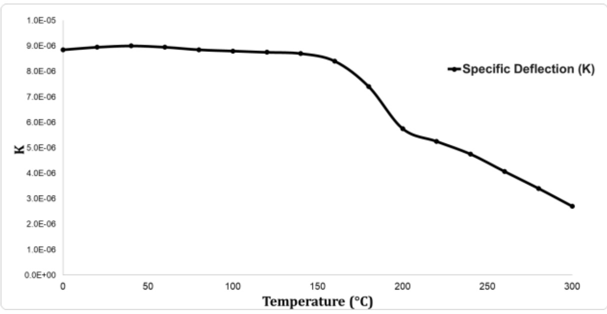

Chart -1: Bimetal-Specific deflection vs Temperature

The response of this bimetallic steam trap was calculated using bimetal design equations, (eq.1), (eq.2), & (eq.3). The theoretical response of the mechanism was plotted along with the saturation curve of steam/water as shown in *Chart-2*. This graph shows a staggered but nonlinear response similar to the saturation curve. Along with this, the theoretical forces generated by the mechanism and the force required for the satisfactory operation of the trap are as shown in *Chart-3*.

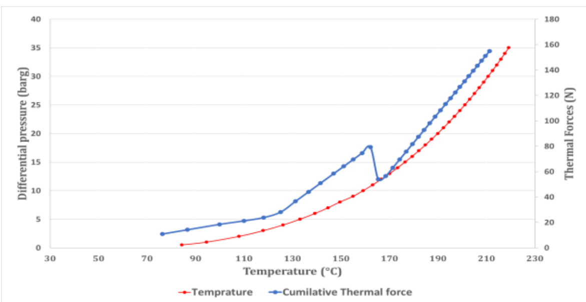

Chart-2: Trap Mechanism – Theoretical Characteristics

An actual prototype of the mechanism was developed based on the inputs from the design calculations and the same was tested. Though the theoretical response obtained and calculation results were satisfactory, when the actual prototype developed was tested, the response obtained was not up to the mark. Leakage of steam was observed from the steam trap. The trap test response is as shown in *Chart-4*. The graph shows that the condensate was not being discharged at a subcooled temperature. The observation was that elements weren't generating enough expansion or forces to overcome the pressure forces needed to close the valve. Further study and analysis were done to find the root cause for this problem.

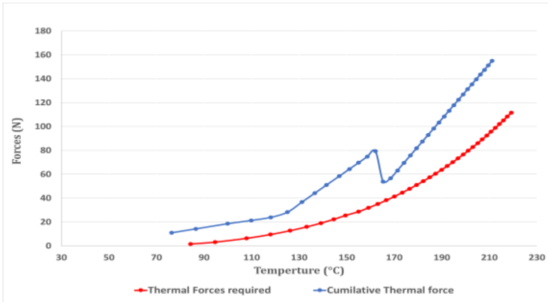

Chart -3: Trap – Theoretical vs Required Force

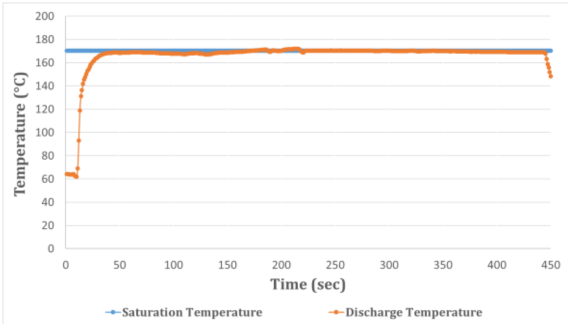

Chart -4: Trap Mechanism – Test response

4. THEORETICAL MODEL & SIMULATION

4.1 Pre-Processing

The mechanism is placed inside an enclosure and body as shown in the rough schematic *Fig-1*. The normally open trap brings hot condensate and steam inside the C_V, around the mechanism. Upon coming in contact with the hot medium, the mechanism expands and closes the valve seat. The valve opens only when the condensate in the C_V cools down and drops below the set temperature or DOS. This is the expected response of a thermostatic bimetallic steam trap.

The reason for the leakage of the steam trap was assumed to be the excessive heat loss from the enclosure and insufficient heat energy within the enclosure for the elements to expand. A natural convection heat transfer CFD study of the trap enclosure was used to validate the aforementioned hypothesis. This helped to find the effective heat loss from the system and calculate the energy available for the mechanism to actuate.

The enclosure that covers the steam trap mechanism is as shown in *Fig-3.* The natural convection CFD simulation was done for selected operating conditions from the entire operating range of 0 barg to 35 barg. The selected points are:

1 barg

10 barg

20 barg

35 barg

The cover is shown in *Fig-3* was divided into 4 parts such as:

1. Top Horizontal surface
2. Cylindrical surface
3. Horizontal Flange surface
4. Cylindrical flange surface

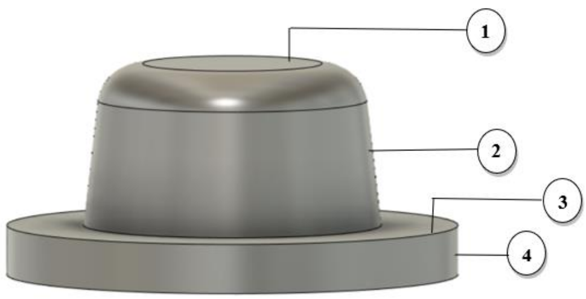

Fig -3: Bimetal steam trap cover

The temperature distribution of the above 4 surfaces was identified through the simulation. This in turn was used to calculate the convective heat transfer coefficient and heat dissipation from the surfaces. The convective heat transfer coefficient was calculated as shown below.

The Nusselt Number equations for the aforementioned types of surfaces for both laminar and turbulent flows are as follows.

The Nusselt number equation for a flat horizontal plate with the hot surface inside and the cold surface outside is:

$$Nu_L = 0.54.Ra_L^{1/4} \text{ , } 10^4 \leq Ra_L \leq 10^7 \qquad \text{(eq.4)}$$

$$Nu_L = 0.15.Ra_L^{1/3} \text{ , } 10^7 \leq Ra_L \leq 10^{11} \qquad \text{(eq.5)}$$

The Nusselt number equation for the outer surface of a cylinder is:

$$Nu_L = 0.47.Ra_L^{0.2} \text{ , } 1.1\text{x}10^7 \leq Ra_L \leq 8\text{x}10^7 \qquad \text{(eq.6)}$$

Here in this equation,

$$Rayleigh's\ Number, \quad Ra_L = Gr_L.Pr \qquad \text{(eq.7)}$$

Where,

Grashoff's Number, Gr_L =

$$Gr_L = \frac{buoyant\ forces}{viscous\ forces} = \frac{g.\beta.(T_{wall} - T_\infty).L^3}{v^2} \qquad \text{(eq.8)}$$

Prandtl Number Pr =

$$\text{Pr} = \frac{momentum\ diffusivity}{thermal\ diffusivity} = \frac{C_p.\mu}{k} \qquad \text{(eq.9)}$$

Where,

g = Acceleration due to gravity (kg.m/s^2)

β = Coefficient of thermal expansion (1/°C)

T_{wall} = Wall Temperature (°C)

T_∞ = Atmospheric Temperature (°C)

L = Vertical Length (m)

v = Kinematic Viscosity (m^2/s)

C_P = Specific Heat (J/kg.°C)

μ = Dynamic viscosity (N.s/m^2)

k = Thermal Conductivity (W/m.°C)

ANSYS FLUENT 16.1, was used to simulate and calculate heat losses from the enclosure. The flow conditions considered for the CFD simulation were 3D, steady & laminar (Rayleigh's number < 10^7). The resultant temperature distribution on the enclosure outer surface (T_{out}) and convective heat transfer coefficient (h_c) was solved based on the conservation equations of mass, momentum, and energy. The equations are:

Continuity Equation:

$$\nabla.(\rho V) = 0 \qquad \text{(eq.10)}$$

Momentum Equation:

$$V.\nabla(\rho V) = \rho X - \nabla p + \nabla^2(\mu V) \quad \text{(eq.11)}$$

Energy Equation:

$$V.\nabla(\rho C_p T) = \nabla^2(kT) \quad \text{(eq.12)}$$

The material properties and boundary conditions are mentioned in the tables given below:

Table -1: CFD simulation model & details

Heat Transfer	Natural Convection (Energy Equation Enabled)
Fluid Medium	Air
Density model for medium	Incompressible-Ideal Gas (Inversely Proportional to temperature)
Flow Type	Laminar (Rayleigh's Number <10^7)
Solid Body Material	Stainless steel

The boundary conditions applied on the geometry taken for CFD studies are added below. The reference is as shown in *Fig-4*:

Table -2: CFD simulation boundary conditions

Pressure Inlet (Face 2 & 3 as shown in Fig.4)	0 barg (Open to atmosphere)
Pressure Outlet (Face 1 as shown in Fig.4)	0 barg (Open to atmosphere)
Cover inner Wall (Face 4 as shown in Fig.4)	Saturation temperature for each pressure point

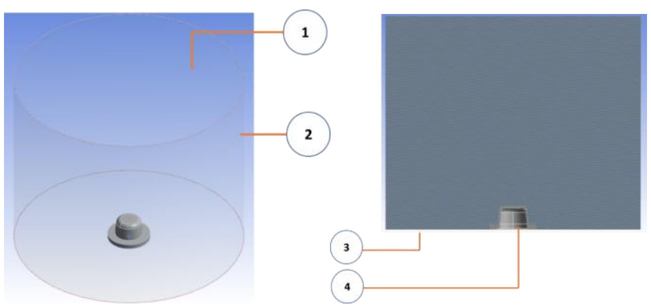

Fig -4: CFD Setup (Boundary Conditions)

Table -3: CFD Pressure & Temperature points.

Pressure (bar g)	Temperature (°C)
1	120.4
10	184.1
20	214.9
35	244.2

The operating conditions for which the CFD study was done are mentioned in *Table-3.*

4.2 Results

The temperature distribution and velocity field results from the CFD study for one selected operating condition from the range (*Table-3*), i.e., 1 barg, are as shown in *Fig-5* & *Fig-6.*

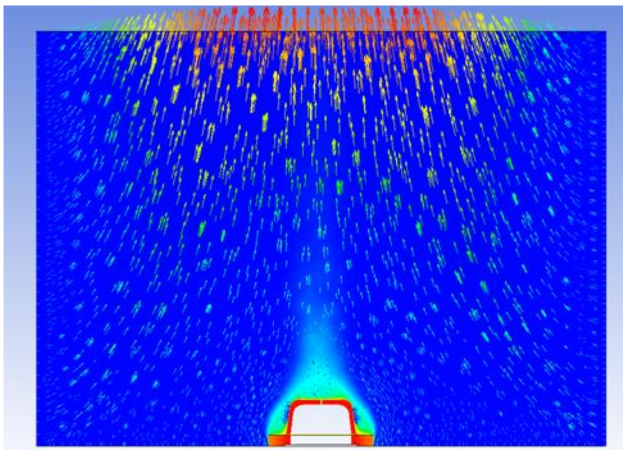

Fig -5: CFD Study-Temperature & Velocity Fields

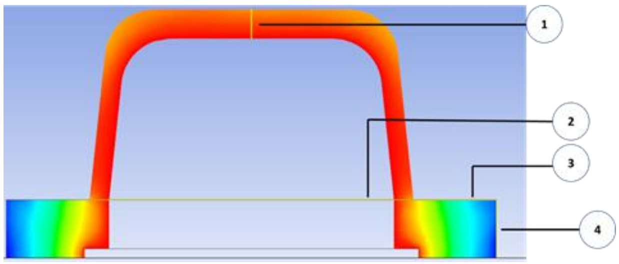

Fig -6: CFD Study-Temperature Distribution

From the T_{out} values obtained from the CFD study, specific temperature values were isolated for the highlighted surfaces as shown in *Fig-3* to calculate the convective heat transfer coefficient. The temperature values of each highlighted surface as shown in *Fig-3* are as marked in *Fig-6*.

The study was conducted for all the selected points and T_{out} values were identified for all those conditions on all the faces/nodes. This study was conducted for cases with saturated condensate flowing through the trap as well as the case with subcooled condensate and the T_{out} values were identified for both cases. The T_{out} variation for the entire operating range for both saturated and subcooled conditions was collected and is as shown in *Chart-5*. The convective heat transfer coefficients at the surfaces were calculated for all the selected study points from the entire range, using the temperature distribution results obtained from the CFD study for both saturated and subcooled conditions.

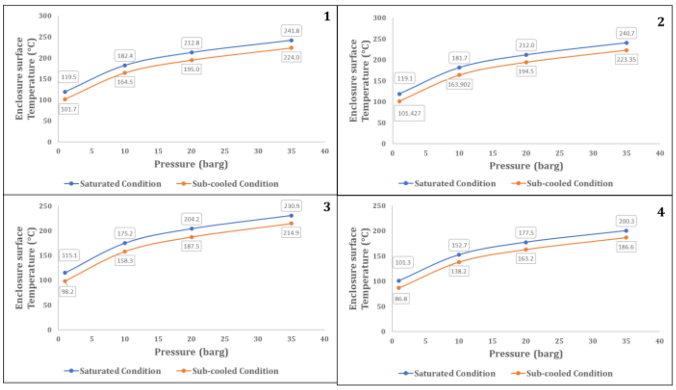

Chart -5: Surface Temperature -Saturated vs Subcooled condition (For operating range)

The convective heat transfer coefficient was calculated based on the equation:

Convective heat transfer coefficient:

$$h_c = \frac{Nu_L . k}{D} \qquad \text{(eq.13)}$$

Where,

Nu_L = Nusselt Number

K = Thermal conductivity

D = Characteristic length (Changes for each surface based on its orientation)

The average convective heat transfer coefficient for the highlighted surfaces was calculated from the T_{out} results obtained from the CFD study. The convective heat transfer coefficient calculated for all faces as per *Fig.4* at one of the operating points, i.e., 1 barg is:

Table -4: Avg. Heat transfer coefficients of faces

Face	Convective Heat Transfer Coefficient (W/m^2.°C)
Face 1	Saturated Condition:- 10.65
Face 2	Saturated Condition:- 05.20
Face 3	Saturated Condition:- 11.60
Face 4	Saturated Condition:- 07.63

The convective heat transfer coefficients calculated as per the (eq.13) for the entire operating range and the highlighted surfaces are as shown in *Chart-6.* This shows the change in the average convective heat transfer coefficient of the external surface of the enclosure over a given pressure range. And overall average convective heat transfer coefficient of enclosure surface.

From the convective heat transfer coefficient values obtained, the effective heat flux or heat loss from the enclosure was calculated using the formula:

Effective Heat loss Flux:

$$\Delta\bar{Q} = \Delta h_c . (T_{Saturated} - T_{Subcooled}) \qquad \text{(eq.14)}$$

Where,

Δh_c = Average heat transfer coefficient from Tout results obtained for both saturated and subcooled conditions

$T_{Saturated}$ = Outer wall temperature at initial condition (Saturated steam/condensate inside the enclosure)

$T_{Subcooled}$ = Outer wall temperature at the subcooled condition for which trap is set (Discharge temperature)

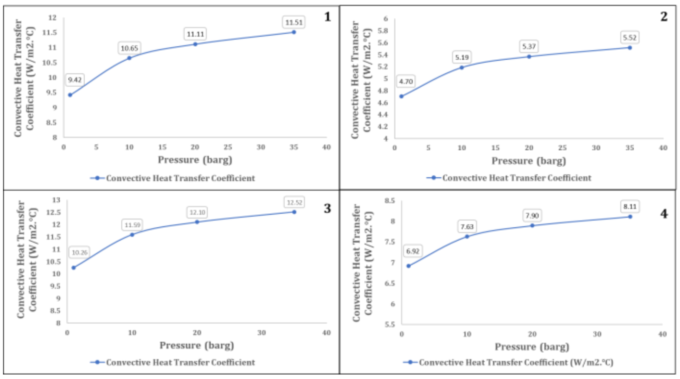

Chart -6: Enclosure Convective heat transfer coefficients

Using the convective heat transfer coefficient obtained from the simulation and using the formula (eq.14), the heat flux at each node of the outer surface/wall was calculated and the average of the same was taken to approximate the total heat lost. *Table.5* shows the heat flux calculated using the post-processor for one of the selected cases from the operating range (i.e., 1 barg)

The above study, calculation, and results were for one selected operating point from the entire operating range. The same was repeated for all the selected operating points from the operating range. The CFD study for saturated and subcooled conditions was done for these selected points using a parametric model and convective heat transfer coefficients were calculated. These values were then used to calculate the effective average heat flux from the cover. Heat loss from the cover throughout the entire operating range was calculated from the heat flux values using (eq.15) and the results are as shown in *Chart-7*.

Table -5: Heat flux values at outer surface nodes from CFD

Node Number	Total Heat Flux (W/m²)		
448	6036.4		
449	6046.5	Average	42781.84
450	6045.4		
451	6024.6		
452	6059.5		
453	6033.3		
454	6048.2		
455	6033.9		
456	6059.9		
457	6051.4		
458	6025.9		

Total Heat loss from cover:

$$Q = \bar{Q} \, . \, A \qquad \text{(eq.15)}$$

Where,

Q = Heat loss (W)

Q = Heat flux (W/m²)

A = Enclosure surface area (m²)

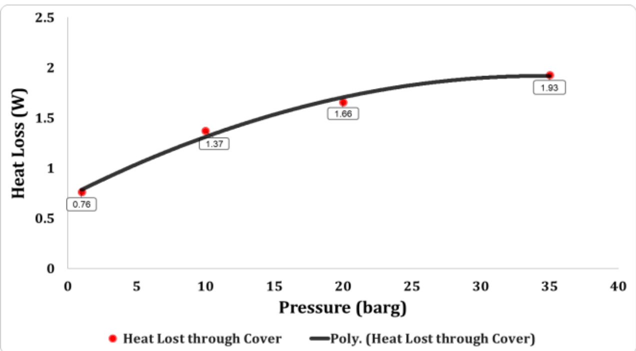

Chart -7: Total heat loss from C_V vs Pressure

The critical volume around the mechanism or effective volume inside the enclosure is the heat energy source and to find the available energy, the total volume inside the enclosure was calculated, and using specific enthalpy of saturated condensate and subcooled condensate, the heat energy available for the mechanism for actuation was calculated.

Total heat available within C_V:

$$Q_{available} = \Delta H \, . \, m \qquad \text{(eq.16)}$$

Mass of condensate inside C_V:

$$m = V . \, v \qquad \text{(eq.17)}$$

Specific Enthalpy Difference:

$$\Delta H = H_{saturated} - H_{subcooled} \qquad \text{(eq.18)}$$

Where,

v – Specific volume of condensate at operating conditions

V – Volume inside the enclosure

$H_{saturated}$ – Specific enthalpy at saturation conditions

$H_{subcooled}$ – Specific enthalpy at subcooled conditions

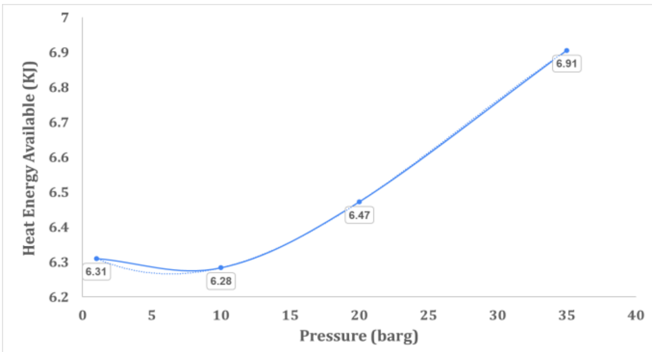

Chart -8: Total Heat energy available vs Pressure

The variation of energy available within control volume across the range is shown in *Chart-8*.

The heat required for the bimetal elements was calculated by coupling the (eq.1) for bimetal expansion, with the specific heat equation. The bimetal expansion equation is expressed as a function of temperature. However, the temperature is not a conserved parameter. Hence, the equation was expressed as a function of heat energy to find the equivalent heat energy required to generate sufficient valve travel and closing forces.

$$D = \frac{a.\text{m.Cp.L}^2}{Q.t} \quad \text{(eq.19)}$$

Considering the forces, the mechanism must generate and the displacements it must produce to perform satisfactorily, the heat energy required was calculated using (eq.19). The total energy required for the satisfactory response of the bimetal mechanism and heat losses from the enclosure was compared with the energy available is as shown in *Chart-9*.

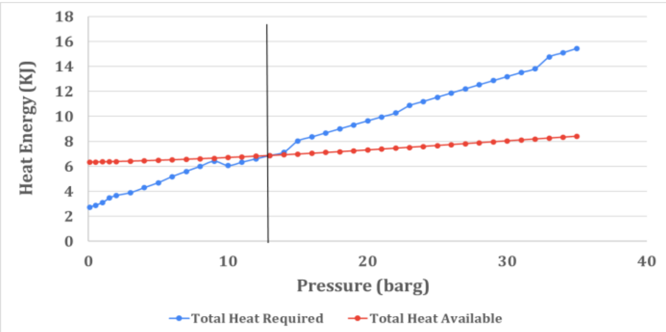

Chart -9: Total Heat available & required vs Pressure

The results from the study show that the available energy is less than the required heat energy for a major part of the operating range. This lack of energy within the enclosure is the reason for the leakage from the steam trap. And the major reason for the jump in energy requirements at higher operating temperatures is the reduction in the specific deflection constant at higher temperatures as shown in *Chart-1*.

Based on the study, it has been proved that the actual heat energy available is limited and hence the mechanism must be designed considering energy as a parameter and not temperature. Mechanism redesign for a given enclosure that meets other design requirements such as pressure vessel norms and strength calculation was done to obtain a satisfactory response.

5. CORRECTIVE MEASURE

Based on the study conducted and calculations done, the actual available energy within the control volume for the mechanism was found. The enclosure around the mechanism is a pressure part/vessel and hence the design calculations for that particular component define the dimensions of the same. Hence the mechanism was redesigned and the actuating elements were restructured and stacked accordingly for this particular cover to obtain ample expansion, valve travel, and valve closing forces.

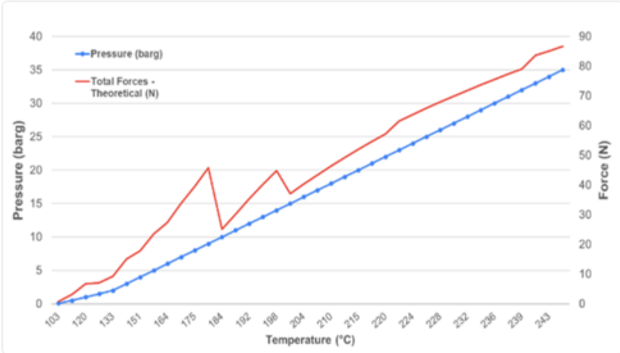

Chart -10: Redesigned Mechanism-Theoretical response

The design calculation for the mechanism was done again and the number of elements and spring was redefined. Based on the new mechanism definition, theoretical trap response characteristics were plotted and thermal forces were checked. The theoretical responses obtained are as shown in *Chart-10* & *Chart-11.*

The new mechanism was developed and tested at various functional test conditions and actual test data was collected to check and validate the mechanism design. The mechanism response was satisfactory and the discharge of the condensate was at an average degree of subcooling and no steam discharge was observed. The response obtained through testing for the redesigned mechanism for one of the test cases is as shown in *Chart-12*. Based on the redefined mechanism's theoretical response and test results obtained, the final mechanism design was found to be satisfactory.

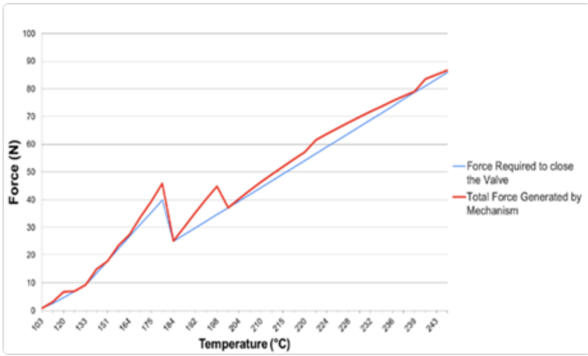

Chart -11: Redesigned Mechanism-Theoretical Force generated and required.

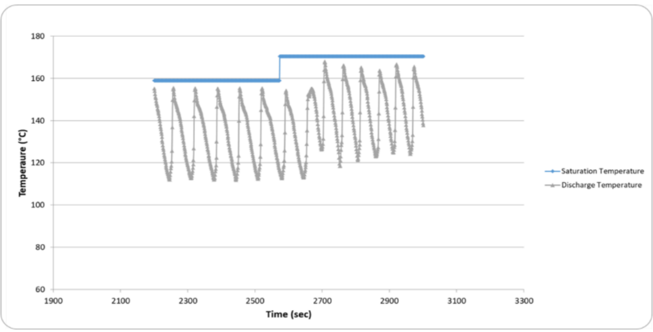

Chart -12: Redesigned Mechanism-Test Results

6. CONCLUSIONS

The mechanism design was finalized through a CFD simulation study and analytical calculations followed by that. Based on the initial calculations, the theoretical response obtained was satisfactory. However, the test results obtained from the prototype weren't up to the mark. Based on the heat-transfer CFD study conducted and calculations done based on the results from simulation, it was identified that the heat losses and energy requirement for the mechanism for actuation were on the higher side compared to the actual heat energy available within the control volume. The mechanism was redesigned with more bimetal elements to obtain a satisfactory response. The same was tested under various operating conditions; results were collected, and the response was found satisfactory.

- A natural convection heat transfer simulation model using commercial software was used to study the trap mechanism and enclosure to identify the effective heat losses from the system.

- The heat losses obtained from the simulation and heat energy requirements obtained from the bimetal element design calculations were compared against the energy available within the control volume.

- The required heat energy is approx. 100% more than available heat energy at higher operating pressures.

- The number of bimetallic elements used in the mechanism had to be increased (15-20% increment) to generate more displacement, valve travel, and valve closing forces, using available energy to operate and actuate the valve efficiently.

- The modified mechanism response was satisfactory based on the calculation results as well as the prototype that was tested for various test conditions.

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BIOGRAPHIES

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