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Optimization and Experimentation of Modified Throttling Calorimeter

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Abstract. Steam plays a vital role in the industrial revolution and is a major source of power generation in steam engines or steam turbine. Thus, it becomes necessary to maintain steam as dry as possible and it is necessary to monitor steam quality on a regular basis. The most commonly used method in determining steam quality is Throttling calorimeter. Here existing throttling calorimeter is designed for determining steam quality within a pressure range of 20 – 25 bar. This existing calorimeter is optimized for monitoring steam quality within a range of 4 – 12 bar gauge pressure. Pipe and orifice dimension of the calorimeter is calculated for a given flow rate of steam by using ISO norms and Bernoulli's principle. After conducting multiple trials on newly designed model test rig it is found that the 4 mm orifice diameter model gives the greater consistency of results and it is considered to be an optimized model.

Keywords: Calorimeter, Dryness fraction, Flow rate, Optimize, Steam quality.

1. Introduction

Steam is the gas formed when water changes its state from the liquid to the gaseous. In steam-using industries, steam is commonly referred to as “Dry or Wet steam.” Steam plays a vital role in the industrial revolution and is the major source for power generation in steam engines or steam turbine. In case of a thermal power plant, if available steam is wet then it results in corrosion and erosion of turbine blades. Thus, it becomes necessary to maintain steam quality high enough and it should be monitored on a regular basis. Hence, steam quality plays a vital role in determining the final product quality and its outcome.

The method used in monitoring steam quality is Tank calorimeter, Separating calorimeter, Throttling calorimeter, Separating-Throttling calorimeter and Electric calorimeter. Based on the availability of inline steam quality, above calorimeters are used for determining dryness fraction of steam.

If available steam is almost dry, we make use of a throttling calorimeter. Here a sample of steam is extracted from the main steam line and passed into the calorimeter through an orifice of known size. Steam throttles at the orifice and finally expands in the expansion chamber of a calorimeter. The overall expansion process of steam takes place adiabatically.

Modified throttling calorimeter is nothing but the modification of existing calorimeter which was designed for monitoring steam quality at 25 bar pressure. Here, existing calorimeter is modified by optimizing overall design of existing calorimeter to some lower size so that it can able to monitor steam quality up to 12 bar pressure. Also, existing model is modified without using a baffle.



1.1 Literature Review

Long et al. [1] described the method for determining the steam quality used in steam flooding for the secondary recovery of petroleum. Here, the convention throttling calorimeter is modified based on available thermodynamic properties of the steam. The process of automatic continuous operation along with heat addition was also described.

Chien [2] described the method of utilizing the pressure at the entry of a nozzle and the flow rate through a nozzle in calculating the quality of steam. The condition required is critical flow through a nozzle and discharge from a nozzle is to be condensed. Amount of condensed steam is measured and using this value steam quality is determined by utilizing standard formula.

Cheung et al. [3] described in detail about the method and apparatus for determining the mass flow rate and the quality of inline steam. In this case, the total flow of steam is directed towards the liquid-vapour separator where some amount of moisture is separated and measured. The flow of one of the stream is regulated to hold the level of the separated liquid constant. Thus, by obtaining the pressure and temperature of the separated flow upstream, the mass flow rate and the steam quality is determined.

Hayes [4] described in detail about how to calculate inline steam quality by using separating calorimeter. He stated that the separating calorimeter helps in removing the moisture content present in the steam that further helps in improving steam quality before it throttles. Here for moisture separation cyclone separator is utilized.

Salunke [5] described the modified throttling calorimeter which helped in improving the performance and obtaining the correct quality of steam. In this case, the overall length of existing throttling calorimeter was reduced and modified by introducing a baffle which helps throttled steam to flow in U-path. The detailed information related to the general principle for methods of measurement and computation of the flow rate of fluid flowing in a conduit by employing pressure differential devices when they are inserted into a circular cross-section conduit running full was obtained through ISO 5167-1 [6].

1.2 Existing throttling calorimeter details

Existing throttling calorimeter shown in fig 1. features baffle plate. Since the throttled steam flow in U-path, the total length of steam travel is increased for the steady flow purpose (velocity profile will get stabilized.) On one side of the baffle, there is a jet of steam with high velocity after an orifice. After traveling some distance it flows to the other side of the baffle with lesser velocity where we can measure steady temperature, pressure.

The overall dimensions of the existing throttling calorimeter model as shown in the Fig. 1:

- 1) Nominal Diameter of the Cylinder body:
 - a) Inner diameter = 154.051mm.
 - b) Outer diameter = 168.275 mm.
- 2) Inlet pipe Nominal Diameter:
 - a) Inner diameter = 15.8mm.
 - b) Outer diameter = 21.34mm.
- 3) Outlet pipe Nominal Diameter:
 - a) Inner diameter = 40.89mm.
 - b) Outer diameter = 48.26mm

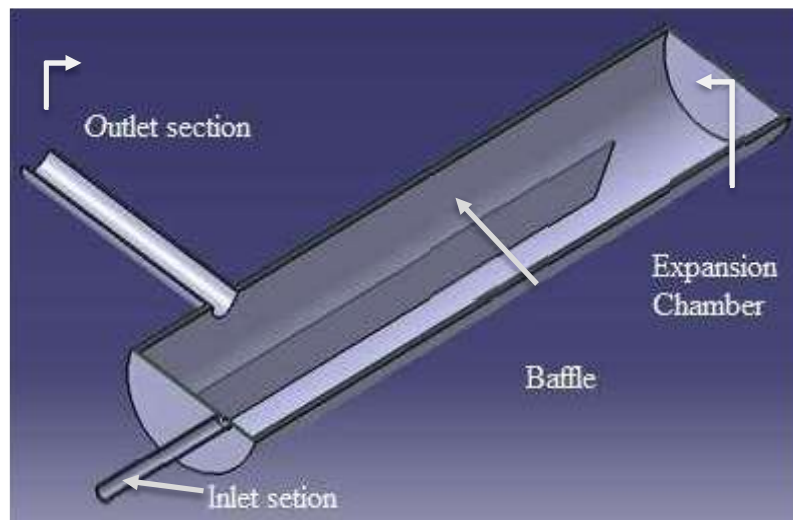


Fig 1. Existing Throttling Calorimeter Sectional View

2. Optimization of Existing Model

2.1 Design of Orifice:

Throttling Calorimeter consists of orifice plate whose purpose is to throttle inline steam. Hence a proper dimension of an orifice is calculated by applying Bernoulli's principle at the inlet section and orifice

$$\frac{P_1}{\rho} + \frac{V_1^2}{2} + gz_1 = \frac{P_2}{\rho} + \frac{V_2^2}{2} + gz_2 \quad \dots\dots\dots (1)$$

Solving above equation, it results to

$$Q_v = \frac{C \times \epsilon \times \sqrt{\left(\frac{2\Delta p}{\rho}\right) \times \frac{\pi D_2^2}{4}}}{\sqrt{1 - \beta^4}}$$

$$Q_m = Q_v \times \rho = \frac{C \times \epsilon \times \sqrt{\left(\frac{2\Delta p}{\rho}\right) \times \frac{\pi D_2^2}{4}}}{\sqrt{1 - \beta^4}} \quad \dots\dots\dots (2)$$

Where,

Q_m = Mass flow rate in kg/hr.

C_d = Discharge Coefficient.

β = Ratio of orifice diameter and internal diameter of inline steam pipe.

D_2 = orifice diameter.

ΔP = Pressure difference.

ϵ = expansion factor = $1 - (0.41 + 0.35\beta^4) \times \frac{\Delta p}{p \times k}$

Given condition

Mass flow rate (Q_m)	=	80 kg/hr
Coefficient of Discharge (C_d)	=	0.61
Inlet Pressure (P_1)	=	1300000 N/m ²
Outlet Pressure (P_2)	=	100000 N/m ²
Density at inlet pressure (ρ)	=	6.62028 kg/m ³
Diameter of pipe (D)	=	0.0158 m

Substituting above values in equation (1) and solving, value of $D_2 = 4.05$ mm.

Thus, orifice diameter for a given mass flow rate and pressure is 4mm and Diameter ratio (β) is 0.2563.

2.2 Calculation of pipe diameter:

For a given orifice diameter, pipe diameter is calculated by using ISO norms. As per ISO 5167 -2 formula for determining pipe diameter is [5]:

$$m_s = 2.73 \times C \times \left(\frac{d}{4.654} \right)^2 \times \left[1 - \frac{P_1 - P_2}{3 \times F_y \times X_r} \right] \times \sqrt{(P_1 - P_2) \times \rho} \dots\dots\dots (3)$$

Where,

P_1 = Primary pressure (kPa abs) = 1300 kPa abs P_2 =

Secondary pressure (kPa abs) = 100 kPa abs d =

Diameter of Orifice (mm) = 4 mm

C = Discharge coefficient = 1

F_y = Specific heat ratio factor = 1.4363

ρ = Density of steam = 6.62028 kg/

X_r = Pressure differential ratio factor = 0.72

By substituting above given values in equation (3), it results to

$$m_s = 126.252 \text{ kg/h} = 0.03507 \text{ kg/s}$$

Since, Specific value of steam (ϑ) = 0.151039 m³/kg and Steam velocity (V) = 25 m/sec

$$\text{Therefore, Area of pipe} = \frac{m_s \times \vartheta}{V} = \frac{(0.03507 \times 0.151039)}{25} = 2.11906 \times 10^{-4}$$

$$\text{Thus, diameter of pipe} = \sqrt{\frac{4 \times 2.11906 \times 10^{-4}}{\pi}} = 16.4 \text{ mm}$$

Hence, nearest standard pipe dimension of 15.8mm i.e. 0.5 inch pipe size is selected.

3. CAD model of modified throttling calorimeter

Referring to the above calculation, the dimensions of orifice and pipe are

i. Orifice diameter = 4 mm.

ii. Pipe diameter = 16.4 mm.

The nearest standard pipe dimension of 15.8 mm i.e. 0.5 inch pipe size (15NB) is selected for modified calorimeter pipe. The CAD model as per above calculated dimension is shown in fig. 2 and fig. 3

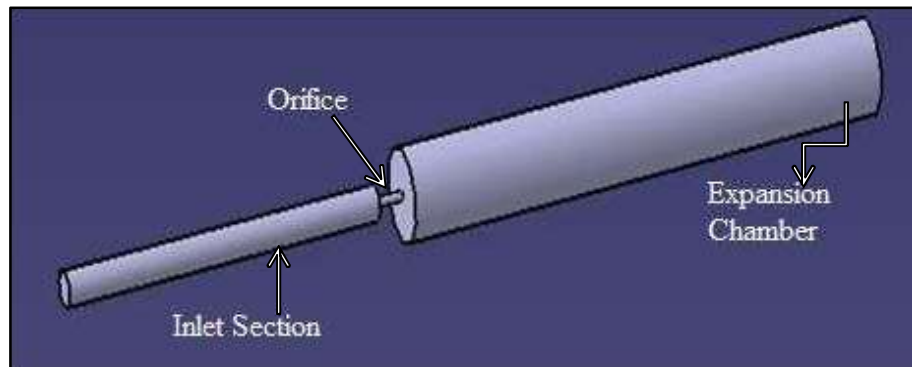


Fig 2. Isometric view of modified throttling calorimeter.

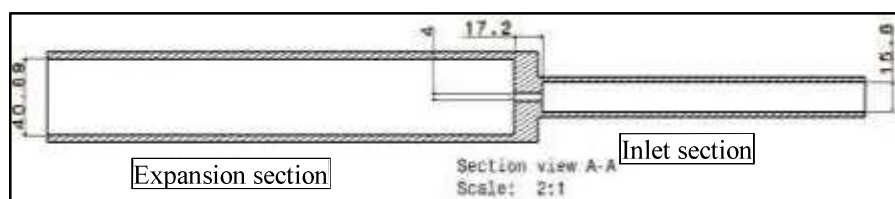


Fig 3. Sectional view of modified calorimeter.

4. Working mechanism and Experimental results

4.1 Operating procedure and layout of modified throttling calorimeter

Step 1: Steam is extracted from the main steam line and is passed to inlet section pipe.

Step 2: Steam is then passed through PRV (Pressure Reducing Valve) and ball valve (BV).

Step 3: After opening the ball valve completely, steam passes through orifice plate where it throttles to atmospheric pressure. Steady state will be observed within 5 to 10 minutes of experiment startup.

Step 4: Note down the pressure and temperature before and after throttling through pressure gauge (PG) and temperature transmitter (TT). By using the steam table, properties of steam are calculated and steam quality is determined.

Working layout shown in fig. 4 describes experimental setup of modified throttling calorimeter. Components included in experimental setup are Pressure Relief Valve (PRV), Ball valve (BV), Pressure gauge (PG 1 & PG 2) and Temperature transmitter (TT 1 & TT 2).

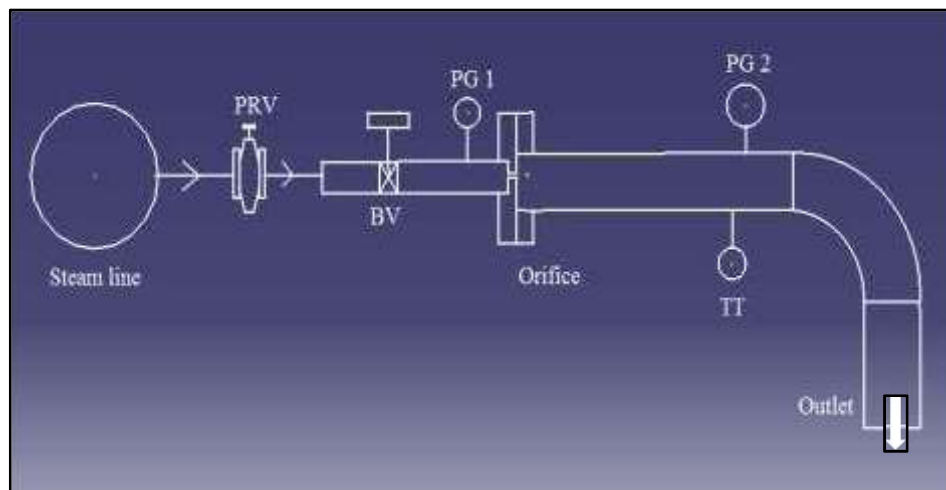


Fig 4. Layout of Modified throttling calorimeter setup.

4.2 Calculation of dryness fraction value

The amount of dryness of steam is determined by equating the enthalpy values i.e. enthalpy of extracted steam at known line pressure and enthalpy of expanded steam in the calorimeter.

After noting down the pressure before and after throttling and temperature after throttling we can able to calculate the quality of steam by using isenthalpic principle as shown below

$$\begin{aligned}
 h_{1v} &= h_2 \\
 h_f + x \times h_{fg} &= h_{sup} \\
 x &= \frac{h_{sup} - h_f}{h_{fg}} \dots\dots\dots (4)
 \end{aligned}$$

4.3 Experimental Results

4.3.1 Dryness fraction of steam calculated with respect to available inline pressure

Results listed in table 1 show the dryness fraction of steam obtained at different available inline steam pressure. Here, different inline pressures are obtained by regulating through pressure relief valve. Thus, through results, it is found that the value of dryness fraction is found to be within the accuracy of 0.5%.

Table 1. Results of dryness fraction value of steam with respect to available inline steam pressure.

P₁(bar)	P₂(bar)	T(°C)	H_{fb} (kJ/kg)	H_{fg}(b (kJ/kg)	H₂ (kJ/kg)	X
4.947	0.997	100.5	638.683	2109.49	2676.84	0.966
5.947	1.047	101.6	669.237	2087.1	2678.45	0.963
6.947	1.097	103.6	696.051	2066.98	2681.94	0.961
7.947	1.097	106.6	720.054	2048.6	2688.16	0.961
8.947	1.147	108.6	741.86	2031.57	2691.68	0.960
9.947	1.197	112	761.895	2015.65	2698.11	0.960
10.947	1.247	113.8	780.471	2000.64	2701.26	0.960

4.3.2 Dryness fraction of steam calculated with respect to boiler pressure

Results listed in table 2 show the dryness fraction of steam obtained with respect to available boiler pressure. Thus, through results, it is found that the value of dryness fraction is found to be within the accuracy of 0.3%.

Table 2. Results of dryness fraction value of steam with respect to boiler pressure.

$P_b(\text{bar})$	$P_2(\text{bar})$	$T(^{\circ}\text{C})$	$H_{fb}(\text{kJ/kg})$	$H_{fg(b)}(\text{kJ/kg})$	$H_2(\text{kJ/kg})$	X_b
7.847	0.997	100.5	717.518	2049.99	2676.84	0.955
8.447	1.047	101.6	730.96	2039.55	2678.45	0.955
9.947	1.097	103.6	761.664	2015.25	2681.94	0.953
10.397	1.097	106.6	770.192	2008.39	2688.16	0.955
11.597	1.147	108.6	791.66	1990.91	2691.68	0.954
12.147	1.247	113.8	800.591	1983.24	2701.26	0.958

5. Conclusions

The following conclusions are drawn from the present work:

1. The expansion chamber diameter of calorimeter is reduced from 154.08 mm to 15.8 mm for range of 4 - 12 bar gauge pressure. Also, existing model is modified without using a baffle.
2. Value of dryness fraction obtained with respect to the available inline pressure was to be within the accuracy of 0.5%.
3. Value of dryness fraction obtained with respect to the boiler pressure was to be within the accuracy of 0.3%.
4. Thus from above experimental readings, it is found that the newly designed throttling calorimeter is an optimized and modified model for determining steam quality within the range of 4 - 12 bar gauge pressure.

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