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Steam Flow Pressure Reduction Valve Mass Flow Calculation

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ABSTRACT

In this paper an analysis of the three different calculation methods for the steam mass flow through the linear pressure reduction valve is presented. Two different makers developed their own mass flow calculation method while one is following recommendation as per ISO standard calculation guidance. All three methods were varied and compared. For calculation model a superheated steam reduction valve was taken, which is reducing superheated steam pressure from 6 to 2 MPa, with fixed K_v value and with variations of the inlet superheated steam temperature from 310 to 280 °C.

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1 Introduction

Steam pressure reduction valves have wide usage in stationary thermal and process plants, but also in the marine propulsion plants [1]. Marine steam plants are rarely in service today due to their lower efficiency compared to the two stroke engines and nowadays may be found mostly in LNG carriers [2]. Reducing steam pressure from the main boiler for the various ship services generates losses which are not obvious with energy analysis, but may be seen by an exergy analysis of the pressure reducing valve [3]. Although pressure reducing generates losses in the system they are required for those systems which are operating at lower steam pressures. Those common ship service systems are used for supplying steam for various feed water heaters, fresh water generators and ship's service [4]. The purpose of reducing the steam pressure is that steam enters to mentioned heaters close to the saturated point as there is no need for such elements to work at higher pressures and where is possible for saturated or slightly superheated steam to convert from steam to condensate. The other function of the steam pressure reducing valve is to control steam mass flow to the desired element of the valve stem position which throttles mass of the steam flow to the final consumer [5]. Also, it is cheaper to build heat exchangers which operate at lower pressure due to material cost, compared to one, which runs at a higher steam pressure [6]. The example of such element is steam air heater for the steam generators [7].

There is variety of pressure reduction valve designs, but the main difference is in their inherent characteristics according to the Figure 1 [8].

The main impact on the flow characteristic curve of the pressure reducing valve has the shape of the valve plug [9] according to the Figure 2. The percentage of the valve lift and the shape of the valve plug determinate mass of steam flow from the inlet to the outlet of the pressure reducing valve.

The main characteristic value of pressure reducing valves is flow coefficient K_V. The flow coefficient K_V is a version of coefficient Cv in mixed SI units. It is a number of cubic meters per hour of water at a temperature between 5° and 40°C that will flow through the valve with a pressure loss of 1 bar at a specific opening position [10]. It is defined by the equation [9]:

$$K_V = Q \cdot \sqrt{\left(\frac{\Delta p_0}{\Delta p} \cdot \frac{\rho}{\rho_0}\right)} \quad (1)$$

where:

Q – m³/h

Δp_0 – reference differential pressure [1 bar]

Δp – operating differential pressure, bar

ρ_0 – density of reference fluid (water = 1000 [kg/m³])

ρ – density of operating fluid, [kg/m³]

As the ratio ρ/ρ_0 is unity (for water), equation (1) is normally given in the form of:

$$K_V = Q \cdot \left(\frac{G}{\Delta p}\right) \quad (2)$$

where:

G – specific gravity, [kg/m³].

In simpler terms, the larger the opening in a valve, the larger the *K*v. As valve opens, the *K*v increases until the valve is fully open, where it reaches its highest possible *K*v, or 100% open *K*v. K_V values for the steam are originally developed and presented by three valve makers mentioned in this article and as such used and compared in this analysis.

Typical steam pressure reduction valve is shown in Figure 3 [11].

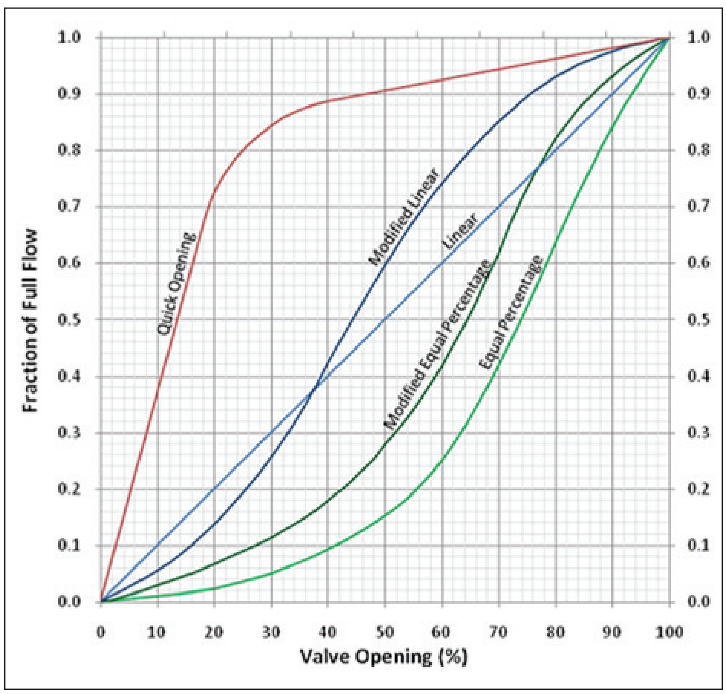

Figure 1 Common types of inherent flow characteristic curves of typical globe valves [8]

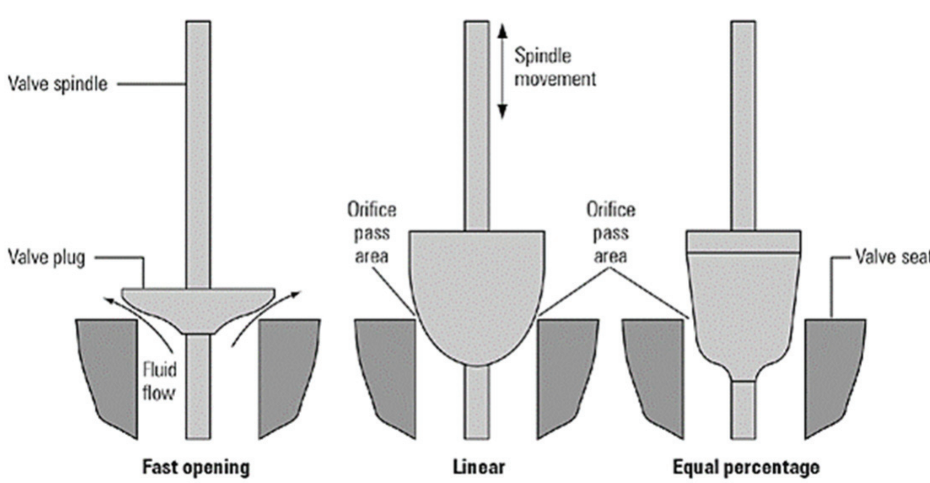

Figure 2 The shape of the valve plug determines the valve characteristics [8]

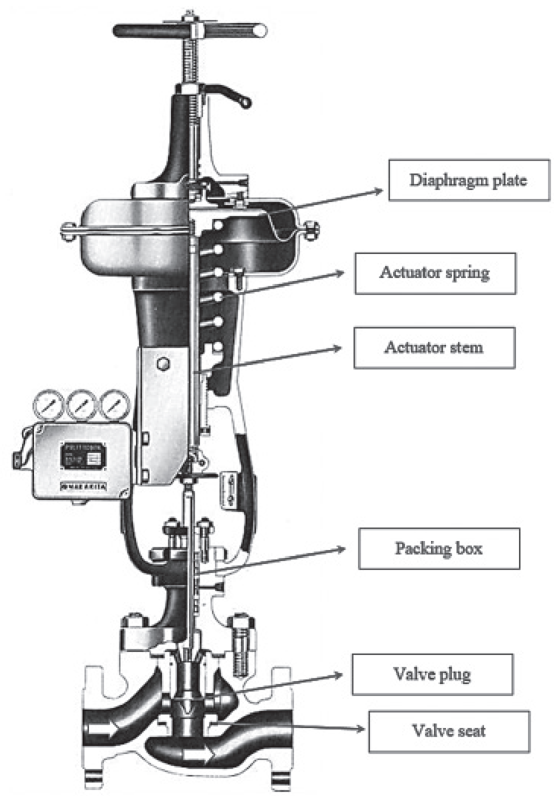

Figure 3 Steam pressure reducing valve [11]

The aim of the pressure reducing valve is to maintain constant pressure at the valve outlet which is set according to process requirements [12]. Simple process valve consists of diaphragm plate, actuator spring and actuator stem. These are power control elements of pressure reducing valve. The air pressure is fed to the top of the diaphragm and stem stroke is regulated by the air pressure which has to overcome the spring force of the pressure control valve. Once when desired pressure is achieved at the pressure reducing valve outlet, then the air pressure, which acts onto the valve diaphragm, and spring force are balanced what results in constant outlet valve pressure. This type of valves are normally used for regulating the flow but can also be used in safety mode. Those type of valves are designed as normally open or normally closed, which depends on process requirements where the pressure reducing valve is employed [13, 14]. For example, in the case of the main marine steam generators when the main boiler reaches high superheated steam temperature, control valves fully open and by-pass steam flow through superheater in order to protect the main turbine from overheating. This is called the failsafe position [15].

The lower part of the valve has an inherent flow characteristic function and according to the valve plug shape it will admit amount of the steam at the pressure reducing valve outlet as previously described in Figure 2. An inherent flow characteristic is the relation between valve opening and flow under constant pressure conditions [16].

2 Three Different Makers Metods for Steam Flow Mass Determination Through the Pressure Reducing Valve

Presented valve has a linear characteristic which is represented by the straight line in the Figure 1. The difference in the flow method calculation is if the pressure drop through the valve is subcritical or supercritical, what is related to the convergent and divergent nozzle theory [17]. The following analysis was made with fixed value of K_v due to subcritical flow through analysed valves. The first analysed method for the steam mass flow is taken from Nakakita maker's recommendation as it is complying with IEC 534-2-1 and IEC 534-2-2 (ISO Standard) [18]. The Nakakita has the following set of equations for the pressure reducing valve mass flow [11]:

$$\dot{m} = \frac{K_{V\,max} \cdot 137{,}66 \cdot \sqrt{\Delta p \cdot (p_1 + p_2)}}{(1 + 0{,}0013 \cdot \Delta t')} \tag{3}$$

if

$$p_2 > \frac{p_1}{2}, \text{ and} \tag{4}$$

$$\dot{m} = \frac{K_{V\,min} \cdot 119{,}31 \cdot p_1}{(1 + 0{,}0013 \cdot \Delta t')} \tag{5}$$

if

$$p_2 \leq \frac{p_1}{2} \tag{6}$$

and

$$\Delta t' = t_2 - t_2' \tag{7}$$

where:

$\dot{m}$ - steam mass flow [kg/h]

p_1 – pressure reduction valve inlet pressure [MPa abs]

p_2 – pressure reduction valve outlet pressure [MPa abs]

t_2 – superheated steam temperature [°C]

t_2' – saturated steam temperature at given pressure

Kv – flow coefficient given from the maker, which is determined by maker's measurements

The second analysed method for the steam mass flow calculation is taken from TLV maker [19], which is another Japanese maker, which developed its own set of equations for the steam flow calculation for the pressure reducing valve mass flow [20]:

$$\dot{m} = 2{,}73 \cdot K_V \cdot \left(1 - \frac{\frac{p_1 - p_2}{p_1}}{(3 \cdot F_y \cdot x_T)}\right) \cdot \sqrt{(p_1 - p_2) \cdot \rho} \tag{8}$$

if

$$\frac{p_1 - p_2}{p_1} < F_y \cdot x_T, \text{ and} \quad (9)$$

$$\dot{m} = 0{,}66 \cdot 2{,}73 \cdot K_V \cdot \sqrt{F_y \cdot x_T \cdot p_1 \cdot \rho} \quad (10)$$

if

$$\frac{p_1 - p_2}{p_1} \geq F_y \cdot x_T \quad (11)$$

where:

$\dot{m}$ - steam mass flow [kg/h]

p_1 – primary pressure [kPa abs]

p_2 – secondary pressure [kPa abs]

ρ – density of the steam [kg/m^3]

F_y – specific heat ratio factor (= specific heat ratio/1,4), [20]

x_T – pressure differential ratio factor (= 0,72), [20]

Kv – flow coefficient given from the maker, which is determined by maker's measurements

The third randomly chosen analysed method for the steam mass flow calculation is taken from Mankenberg maker [21], which is a German maker, which again developed its own set of equations for the steam flow calculation for the pressure reducing valve mass flow [22]:

$$\dot{m} = K_V \cdot 461 \cdot \sqrt{\frac{\Delta p \cdot p_2}{t_1 + 273}} \quad (12)$$

if

$$\Delta p > \frac{p_1}{2}, \text{ and} \quad (13)$$

$$\dot{m} = \frac{K_V \cdot 230 \cdot p_1}{\sqrt{t_1 + 273}} \quad (14)$$

if

$$\Delta p > \frac{p_1}{2} \quad (15)$$

where:

$\dot{m}$ - steam mass flow [kg/h]

p_1 – inlet pressure [bar abs]

p_2 – outlet pressure [bar abs]

t_1 – temperature at inlet [°C]

Kv – flow coefficient given from the maker, which is determined by maker's measurements

Although other makers were not considered in this paper it is worth to mention that Spirax Sarco for some simpler solutions includes mathematical best fit method where it is assumed that critical pressure drop occurs in 58% of the upstream pressure [9].

3 Analysis Results

In this analysis a calculation model of superheated steam reduction valve was used. Steam pressure was reduced from 6 to 2 MPa with variations of the inlet superheated steam temperature from 310 to 280 °C. All necessary data were calculated by using NIST-REFPROP 9.0 software which uses data from [22, 23]. Only superheated steam is analysed in this paper in order to avoid saturated phase area. For validation purposes saturation temperature of 212.38 °C is obtained using NIST-REFPROP 9.0 software and 211.47 °C with the following equation for 2 MPa [24]:

$$t_s \approx \sqrt[4]{p_1} \cdot 100 \quad (16)$$

where p_1 is pressure (abs.) in bar [24].

Figures 4 to 7 show the relation between steam mass flow and percentage of pressure reduction valve opening of three different valve makers (Nakakita, TLV, Mankenberg). Superheated steam temperature was reduced from initial 6 MPa to 2 MPa and temperature was decreased by 10 °C, from 310 °C until the final value of 280 °C was reached under fixed pressures and Kv values.

According to the analysis results it can be seen that as the superheated inlet steam temperature decreases, mass flow of the superheated steam increases through the steam pressure reducing valve. As Nakakita steam pressure reducing method is complying with the ISO references for the pressure reducing valve flow calculation, it may be taken as the reference value in the analysed results. The highest discrepancy from the reference values is according to the third formulation method (Mankenberg) where discrepancy is higher as the inlet temperature decreases. The second method (TLV) is giving similar results at 290 °C, but at the other calculating values differences are higher. The impact in balancing of the steam power plant with different maker's calculation approach may affect proper mass balancing of the analysed power plant where the error in the mass flow will be higher with higher steam flow through the reduction valve.

The discrepancy in absolute steam mass flow values from the first method, which complies with ISO recommendation of the superheated mass flow calculation of the reduction valve, in comparison with the other two methods are given in Table 1 and relative flow discrepancy is calculated according to [25].

$$\delta x = \frac{\Delta x}{x} = \frac{x_0 - x}{x} = \frac{x_0}{x} - 1 \quad (17)$$

where:

x_0 – compared value and

x – reference value.

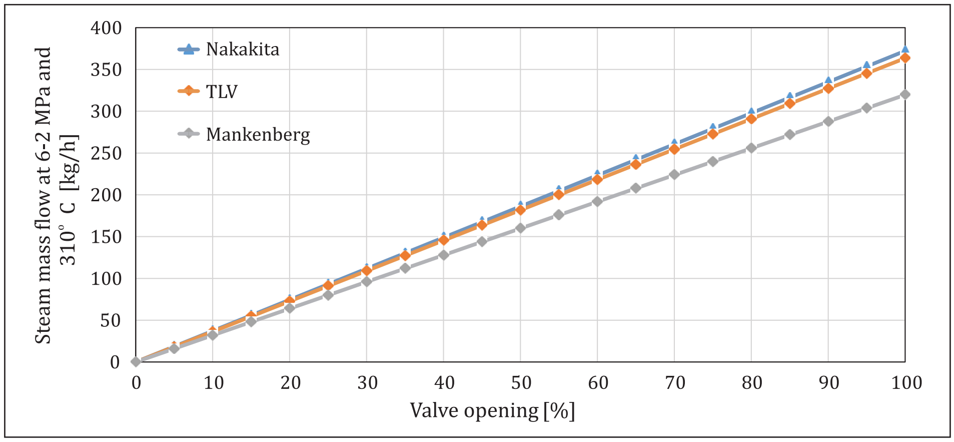

Figure 4 Steam pressure reducing valve flow from 6-2 MPa at 310 °C

Source: Authors

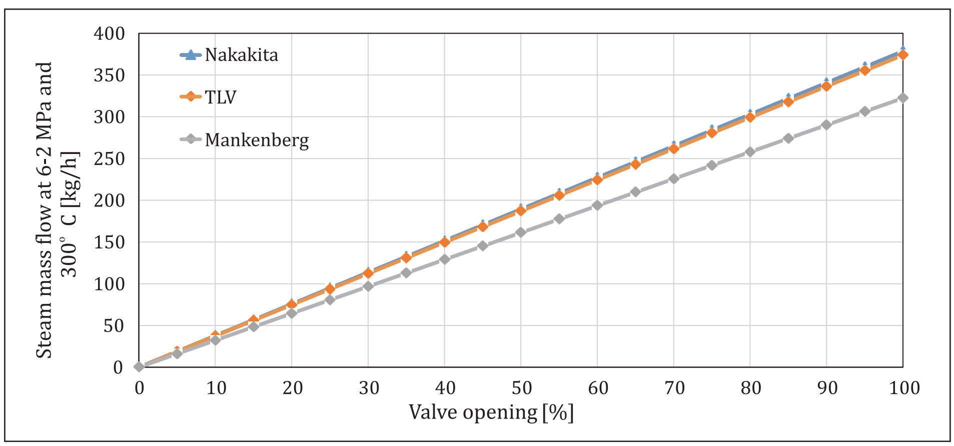

Figure 5 Steam pressure reducing valve flow from 6-2 MPa at 300 °C

Source: Authors

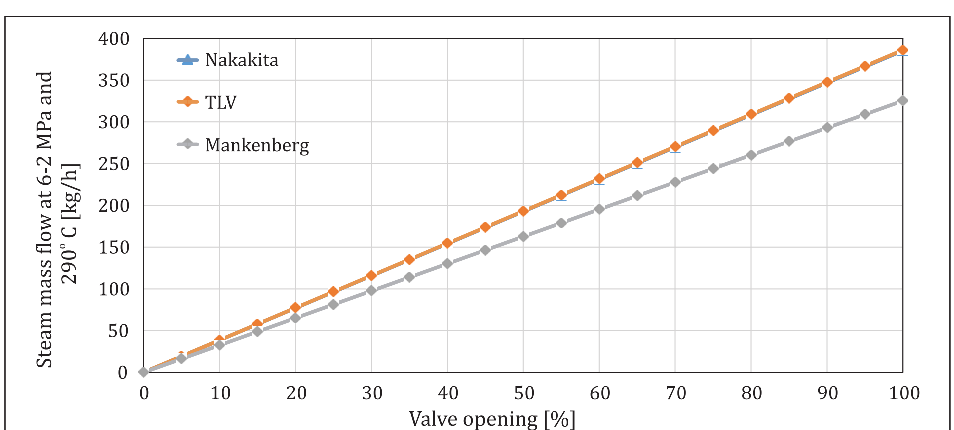

Figure 6 Steam pressure reducing valve flow from 6-2 MPa at 290 °C

Source: Authors

Table 1 Steam flow deviation from the ISO standard recommendations

Method results	Pressure reducing range	Inlet temperature	Relative flow discrepancy in [%]
TLV	6 to 2 MPa	310 °C	-7.76
Mankenberg			14.12
TLV		300 °C	-8.61
Mankenberg			14.83
TLV		290 °C	-9.76
Mankenberg			15.59
TLV		280 °C	-11.41
Mankenberg			16.40

Source: Authors

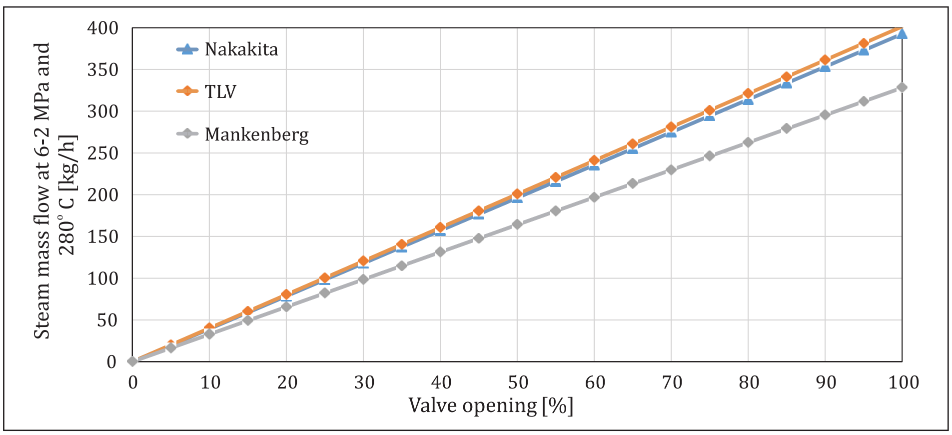

Figure 7 Steam pressure reducing valve flow from 6-2 MPa at 280 °C

Source: Authors

Figure 8 shows pre-set inlet temperatures and calculated outlet temperature from the pressure reduction process inside the valve at h = const, [26]. As superheated steam temperature decreases at the inlet of the steam pressure reducing valve, temperature difference $\Delta t = t_{in} - t_{out}$ is higher and is approaching to the saturation line faster.

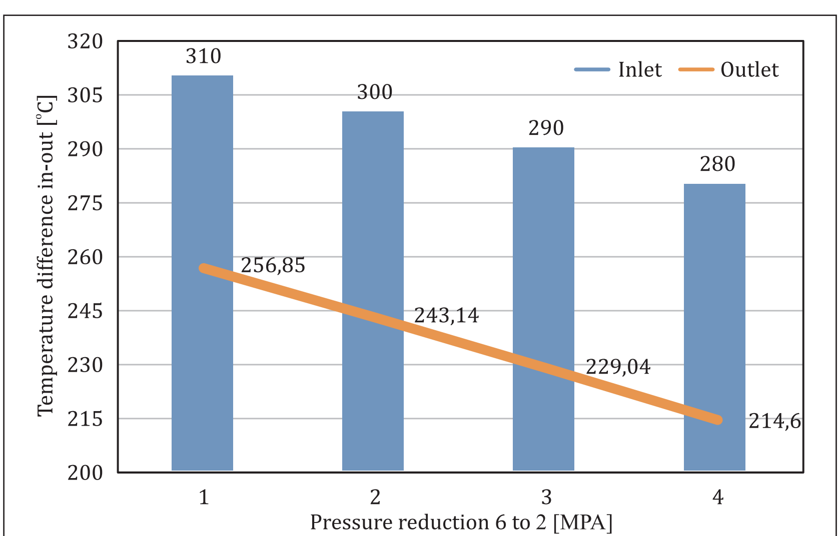

Figure 8 Temperature drop with inlet temperature variation at fixed pressure reduction

Source: Authors

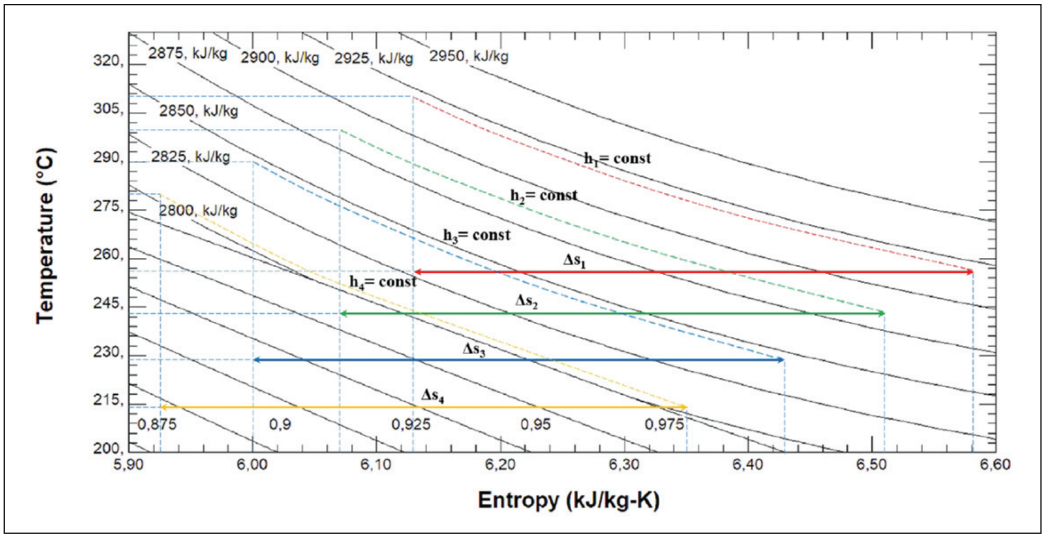

Figure 9 Entropy increase with passing through superheating steam reduction valve

Source: Authors

As throttling process goes under constant enthalpy, theoretically that is ideal process. However, as per Figure 9, entropy generation is present in such processes. In the analysed process, entropy generation at the 310 °C is higher comparing to the entropy generation at the lowest observed temperature of 280 °C and exergy efficiency will be higher at the lower inlet temperatures due to $\Delta s_1 > \Delta s_4$.

4 Conclusion

In this paper the three different maker's pressure reducing valves were analysed. Superheated steam temperature was reduced in Nakakita, TLV and Mankenberg valves from initial 6 MPa to 2 MPa and temperature was decreased from 310°C till 280 °C.

Analysed results show that as the superheated inlet steam temperature decreases, mass flow of the superheated steam increases through the steam pressure reducing valve.

Nakakita steam pressure reducing method, which is complying with the ISO references, was used as the reference value in the analysed results. The highest discrepancy from the reference values is according to the Mankenberg formulation method where discrepancy is higher as the inlet temperature decreases. Different calculating methods may affect proper mass balancing in power plants and cause discrepancy in mass flow through the reduction valve.

The energy efficiency of the pressure reducing valve is constant due to the same isentropic flow at the inlet and outlet of the steam pressure reducing valve, as per [26]. However entropy generation is present in such process which causes higher exergy efficiencies at lower inlet temperatures.

Although presented analysis gives results which may compare the differences in the mass flow amount, it has to be bared in mind that makers possible will not give full details of calculation method and formulas as they are protecting their copyrights.

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