Entropic Analysis of Processes in Control Valves

IOANA DIACONESCU
Department S.I.M.
Engineering and Agronomy Faculty of Braila
“Dunarea de Jos” University of Galati
Calea Calarasilor nr. 29, Braila
ROMANIA

Abstract: - The thermodynamic analysis of irreversible processes has an important influence in energy efficiency growing of any thermodynamic processes or systems. All of thermodynamic processes are entropy generators but there are processes with such a high level of irreversibility so that couldn’t be ignored. That is why is so important to identify what causes entropy generation and also to identify those system components that contribute the most to the overall irreversibility of the thermodynamic system. One of the processes with the highest level of entropy generation is flow with friction in various ducts and flow networks such as control valves. In order to see the direct connection between frictional pressure drop and thermodynamic irreversibility the paper will firstly analyze the steady and adiabatic flow of pure substance through a short segment of pipe with variable section (control valve).

Because the entropy generation value during the throttling process is proportional to control valve pressure drop, the paper will do a flow thermodynamic analysis inside the control valve and the conclusions about drop pressure in different working conditions will be taken. Pressure drops along a valve are not constant, but rather vary in relation to the port left open by the plug. They normally increase as the valve narrowest section is reduced, although the upstream drop does increase at a slower rate than the downstream one. Actual increases and decreases in pressure drop and their effects are related to valve type and flow direction. It can be deduced that, for all types, pressure drops increase at flow tending to close, mainly as a result of the increased drop generated downstream.

Also, the paper will take into account the drop pressure variation during the substance flow and will be analyzed its influence on the process irreversibility.

In the same time, the paper will analyze the change of state influence during the liquid throttling process on the entropy generation, in situations of low titer bipolar phase fluid or high titer bi-phase fluid and will identify this phenomenon effects and remedies.

Key-Words: entropy, control valves, throttling, flow, irreversible process, pressure drop

Received: May 23, 2022. Revised: January 7, 2023. Accepted: February 13, 2023. Published: March 27, 2023.

1 Introduction

The thermodynamic analysis of irreversible processes has an important influence in energy efficiency growing of any thermodynamic processes or systems. All of thermodynamic processes are entropy generators but there are processes with such a high level of irreversibility so that couldn’t be ignored. That is why is so important to identify what causes entropy generation and also to identify those system components that contribute the most to the overall irreversibility of the thermodynamic system. One of the processes with the highest level of entropy generation is flow with friction in various ducts and flow networks such as control valves. In order to see the direct connection between frictional pressure drop and thermodynamic irreversibility the paper will firstly analyze the steady and adiabatic flow of pure substance through a short segment of pipe with variable section (control valve).

The entropy of a system is a state size that measures the degree of irreversibility of the system, it cannot decrease, it remains constant if only reversible processes are carried out in the system, and it increases if irreversible processes take place in the system. If in the initial state the system is in internal thermodynamic equilibrium, entropy will remain constant over time. If the initial state of the thermodynamic system is of thermodynamic imbalance, irreversible spontaneous processes are carried out in the system, which tend to bring the system into a state of thermodynamic equilibrium, in which case the entropy will increase, tending to a maximum final value. Once this value is reached, the system will remain in balance until the insulation is lifted. In an isolated system, equilibrium involves equalizing the temperatures of all the bodies that make up the system, and after establishing the equilibrium, it is no longer possible to convert heat into mechanical work in the system, because there are no heat sources of different temperatures. Thus, the increase in entropy of an isolated system is a measure of the degradation of energy, that is, the reduction of the capacity of producing work within the system.

Also, the entropy of a system varies either due to the transport of entropy from the system to the environment or from the environment to the system, or by generating entropy in the system during the thermodynamic transformations specific to the thermal equipment that make up the thermodynamic system. The variation in external entropy may be positive, negative, or null depending on the system's interaction with the environment.

Entropy created in the system is always positive because during irreversible processes entropy is generated.

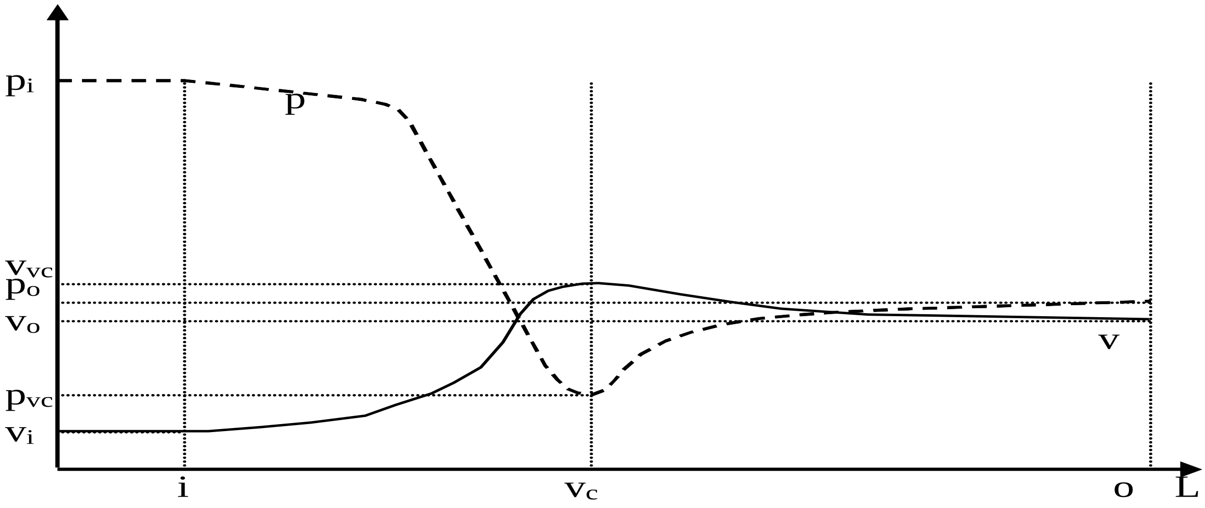

Fig. 1 Pressure and velocity variations

The paper analyzes the generation of internal entropy in the throttling process that takes place in the control valves. This type of irreversibility is defined to be internal irreversibility and occurs over the thermodynamic processes characterized by: friction between the working agent and the physical components of thermal machines, friction between the layers of heat, turbulence and homogenization in the agent that participates in the transformation of energy from one form to another.

2 Throttling

Control valves have variable section orifices which create localized pressure drops. A fixed reducer whose valve narrowest section pressure is way below final pressure can be examined at a certain opening value (figure 1).

Likewise, plotting fluid velocity shows that the valve narrowest section has its minimum p value when the v value is at its maximum. The transformation that the fluid undergoes between the upstream section and the valve narrowest section is extremely rapid and does not entail heat exchanges. In the absence of vortices, it would thus result as isentropic. Similarly, the transformation downstream with no drops appears isobar, and restores the fluid to starting enthalpy conditions [1,12].

In fact, the first branch of transformation, resulting in continual rapid conversion of pressure energy into kinetic energy, occurs at rising entropy, due to inevitable friction losses. The second branch of the curve, when the valve narrowest section pressure goes below the final value (still at rising entropy), consists of a compression. Downstream of the reduced section, the fluid is considerably accelerated. Since, however, downstream and upstream velocities must be approximately equal, intense vortices are generated and can endure eve up to valve outlet. The kinetic energy acquired by the fluid during throttling is turned into heat in the vortices. Also, the greater the compression, the more intense are the ensuing vortices. Whereas the transformation, mostly isenthalpic, of ideal fluids does not produce temperature variations, ideal fluids are cooled by throttling [2,12].

Cooling gradually increases as the fluid approaches the valve narrowest section, and is then attenuated as a result of both compression and the effect of the vortices. Reverse temperature changes affect the specific gravity, which initially increases until it reaches maximum in the valve narrowest section and then, as the effect of compression prevails over friction heating, decreases.

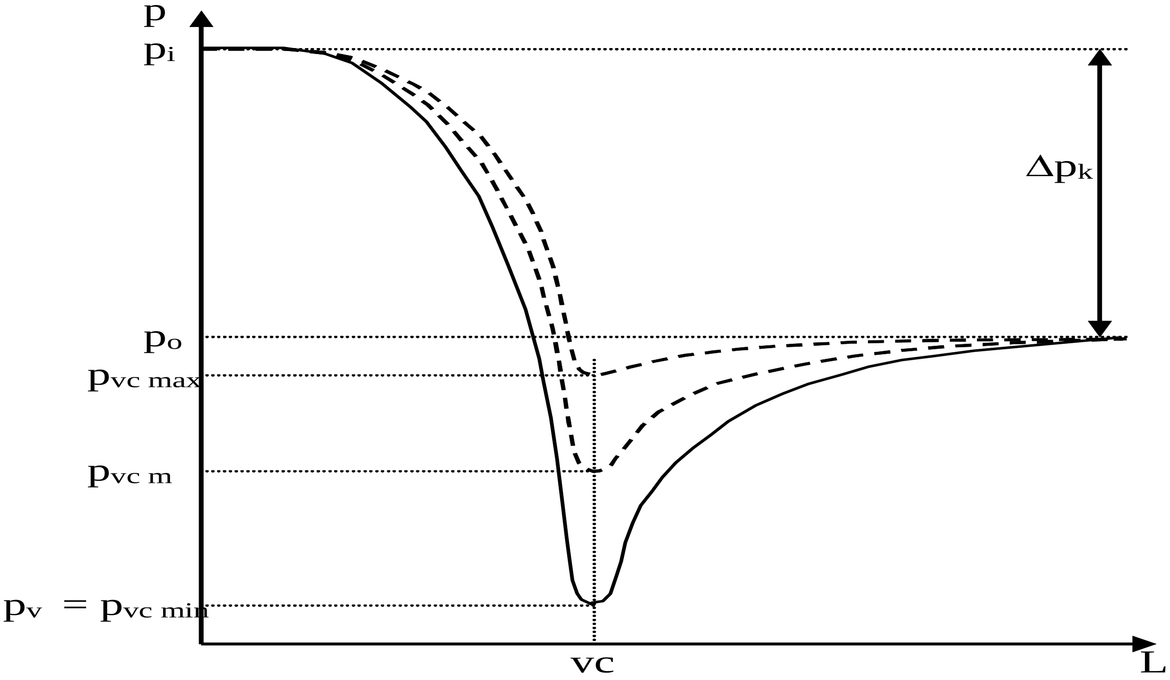

Fig. 2 Pressure variation

In actual practice, determining the valve's typical behavior and plotting the transformation on a state diagram allows us to express the foregoing considerations in terms of quantity.

3 Typical valve factors

The pressure that reached in the valve narrowest section can be calculated using the pressure recovery factor when both upstream and downstream pressure is known. F is not a constant, but varies as to aperture. A low recovery factor means that much lower pressures are reached in the valve narrowest section than at outlet, making it an easy matter to reach critical flow conditions. On the other hand, a recovery factor approaching one is equivalent to having the valve narrowest section and downstream pressures approximately equal.

A first approximation of F expressed as:

$$p_{vc} = \frac{1}{F^2}\left[p_o - p_i\left(1 - F^2\right)\right] \tag{1}$$

allows selection of the valve type, or better, makes it possible to establish the minimum value of F compatible with design conditions p_i and p_o. In fact, since p_{vc} must be greater than zero, this condition occurs if:

$$F > \sqrt{\frac{\Delta p}{p_i}} \tag{2}$$

The F factor is important in liquid-flow valves where critical flow conditions are reached when the pressure in the reduced section reaches the vapor tension corresponding to the temperature in the valve narrowest section. Reaching critical conditions means that the valve is crossed by a bi-phase (liquid + vapor) fluid. This results in limited flow capacity and creates the conditions that bring about cavitations. Actually, $p_{vc} > p_v$ is not a 100% guarantee that criticality state will be absent. Local conditions, depending on how complex the trim and body geometry are, can be such that vaporization pressures are reached in the valve narrowest section, or even along the upstream flow path [3,12].

As a result, upstream pressures being equal, flashing and cavitations can start to appear with downstream pressures greater than those calculable from the recovery factor. In order to be absolutely sure that cavitations conditions will not be encountered, the incipient cavitations index K, defined as:

$$K = \frac{\Delta p_k}{p_i - p_v} \qquad (3)$$

makes it possible to calculate the maximum value of $\Delta p = \Delta p_k$ that is compatible with a stated p_i.

This is equivalent to attributing to the valve the same recovery factor as that of the fluid fillet's most critical flow path (fig. 2).

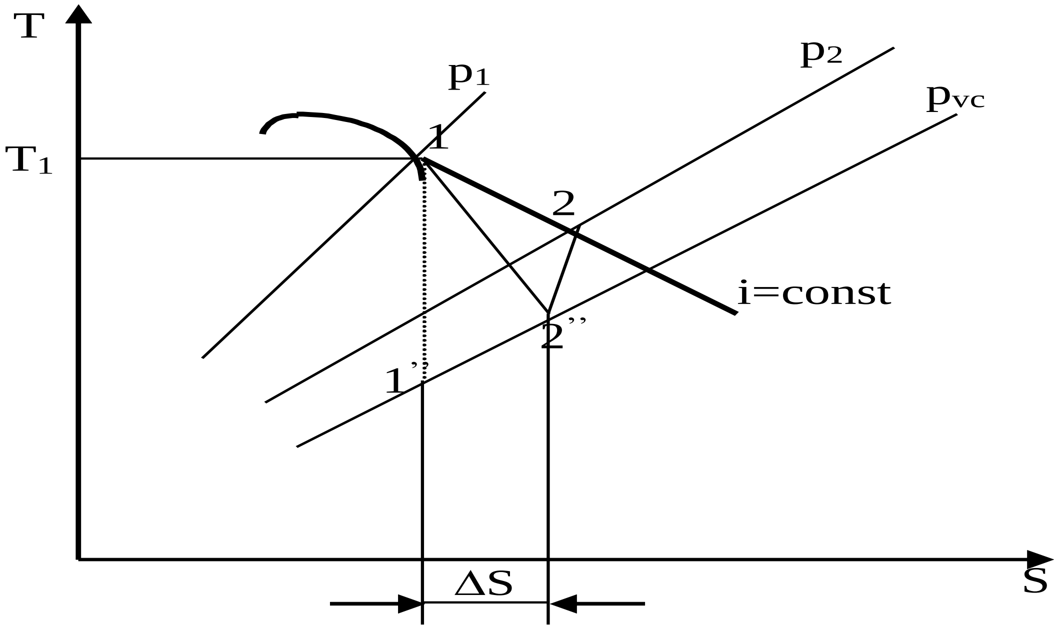

Fig. 3 Process on state diagram

4 State Diagrams

State diagrams represent the physical conditions that a substance assumes as its thermodynamic state varies. Sets of states may be shown on graphs as functions of parameter pairs (p and v, T and S, i and S, p and S, etc.), and are divisible into areas of homogeneous physical states [4,12].

The most commonly used state diagrams have entropy or enthalpy for the abscissa and temperature, enthalpy, or pressure, for the ordinates.

In chart (p,v), isotherm T_{cr} corresponding to critical temperature, is the lower limit of the pure gas region and shows the maximum temperature at which aero forms can be liquefied. T_{cr} is tangential to a single-dome parabola curve at point C, designated critical point, which corresponds to pressure p_{cr} and constitutes the pressure at which an aero form at T_{cr} can be liquefied. The left and right slopes of the parabola are designated respectively lower limit curve and upper limit curve. The lower curve with isotherm T_{cr} delineates the area where liquids are to be found, whereas the area enclosed between the upper limit and isotherm T_{cr} is the region for superheated steams. The two limit curves mark off the saturated steam zone where the liquid is in equilibrium with its vapor. The fluid's thermodynamic state in this region is obtained by use of only a single parameter (either pressure or temperature), and the variations in v along the isobar and isotherm curves are justified by the varying of the liquid-vapor mass ratios (titer x).

5 Thermodynamics Representative Processes on State Diagrams

The first transformation phase undergone by a fluid inside a valve is adiabatic expansion from the state characterized by pressure p_1 and temperature T_1 at pressure p_{vc} (fig. 3).

In the absence of friction (reversible transformation), the final state would be represented by point 1' and the fluid would accumulate all expansion work in the form of kinetic energy. In actual practice, however, since friction heat is present, the fluid is dilated and has a specific volume corresponding to that at point 2".

Consequently, even though no heat exchanges with the outside occur, there is an increase in ΔS entropy. Transformation is thus adiabatic, and not isentropic. Shown on the entropic plane (T-S), it may be expressed as a polytropic curve passing through initial state 1 and final state 2” [7,12].

Similar considerations may be expressed regarding the second transformation phase undergone by the fluid between the valve narrowest section and the downstream zone. If no friction and recovery existed, then transformation would be isobar. Actually, though, it consists of a compression from valve narrowest section state 2” to final state 2 and, without considering heat exchanges with the exterior, may still be taken as adiabatic [5].

6 Remarks on Pressure Drops

Pressure drops along a valve are not constant, but rather vary in relation to the port left open by the plug. They normally increase as the valve narrowest section is reduced, although the upstream drop does increase at a slower rate than the downstream one. Actual increases and decreases in pressure drop and their effects are related to valve type and flow direction. It can be deduced from the F values that, for all types, pressure drops increase at flow tending to close, mainly as a result of the increased drop generated downstream [8].

Assuming an upstream drop of zero is equivalent to considering the upstream expansion isentropic at the valve narrowest section while, on the contrary, a zero drop downstream means that the compression phase is isentropic from the valve narrowest section downstream. Although upstream drops in control valves normally fail to be considered, this does not lead to grave errors. Nevertheless, in the case of vaporizing fluids, such simplification may turn out to be overly optimistic and risky. In fact, it is obvious that throttling affecting liquids near the limit curve could mistakenly seem to be free of cavitations.

Vice versa, assuming the transformation at the downstream pressure drop as zero would result conservative from the valve capacity standpoint, but quite onerous in terms of cost. In actual practice, valve narrowest section entropy falls midway between the fore mentioned pair of limit values, and is related to valve type. Once valve narrowest section conditions have been established with S_{vc} and p_{vc}, even if the compression transformation of a vaporizing fluid is at rising titer, there is no guarantee that cavitations does not exist.

From the foregoing considerations, it is evident that cavitations is totally lacking when the compression transformation at increasing titer, whose valve narrowest section is determined by S_{vc}, is

$$p_{vc} = p_i - \frac{p_i - p_o}{K} \qquad (4)$$

where K = index of incipient cavitations.

7 Effects of Pressure Variations

Once the constancy of the valve’s typical factors at a specific aperture has been established, it is easy to deduce behavior as upstream and downstream pressures vary.

Downstream p_o pressures being equal, the increase in upstream pressure lowers the valve narrowest section pressure. Thus, a liquid throttled so that its physical condition upon reaching the valve narrowest section corresponds to conditions at the lower limit curve will start cavitations process from small p_i increases.

On the other hand, even small upstream pressure reductions can serve to sidestep the danger of critical operation.

Having established that cavitations is avoided when the fluid from the downstream valve narrowest section has a curve not greater than the isotainer and knowing the operating pressures, the limit value of K able to prevent cavitations from arising may be determined. Upstream pressures p_i being equal, downstream pressure drops causes corresponding pressure drops in the valve narrowest section, whereas increases in the p_o have the reverse effect, and hence are similar to those described for the p_i variations.

8 Liquid throttling

Knowing the conditions of the upstream liquid (p_1 and t_1) and the pressure desired downstream (p_2) use of a valve having a stated F allows determination of the valve narrowest section pressure [10].

The transformation results at a slightly decreasing temperature and gradually increasing specific volume. The final transformation point (2), with $i_1=i_2$, has a temperature close to t_1 and a specific volume v_2 very similar to v_{vc}. Transposing points 1 and 2 onto the fluid state chart, the limit value of F bringing the valve narrowest section pressure to vaporization conditions can be deduced. Thus, considering the slope of the vc-2 transformation, the presence of cavitations cannot be excluded [6,12].

In order to prevent the cavitations from arising it is necessary to roughly limit the upstream-downstream Δp to a value calculable using the incipient cavitations index K formula. Nevertheless, the possibility that vaporization pressure fails to be reached does exist. In fact, as valve narrowest section pressure is the function of the temperature generated by expansion, if the calculated p_{vc} is lower than p_v, it continues to vaporize at constant pressure until the pressure starts to climb again due to the effect of recovery.

When required downstream conditions correspond to a point on the lower limit curve, occurrence of cavitations is practically inevitable and, in similar types of valves, the higher the temperature, the greater the fluid fraction affected. To avoid such macroscopic cavitations, transformation branch vc-2 has to coincide with a section of the limit curve, and thus F must be close to one. Furthermore, to ensure that cavitations is completely absent, the valve must have $K \approx 1$[9,12].

In fact, at low temperatures, the isenthalpic and isentropic curves overlap, and the iso-titer curves have steeper slopes than at high temperatures.

The fluid temperature reaches in the valve narrowest section is usually lower than the upstream temperature, and this difference increases at t_1 and the required Δp increases too. Although similar considerations hold true for the downstream temperature, the differences are not as marked.

Specific volume, which rises gradually from v_1 to v_2 for $F \approx 1$, can even be several times v_1 in the valve narrowest section if the recovery factor is low and Δp high.

With the exception of valves in which $K \approx 1$, when point 2 is on the lower limit curve, the downstream specific volume is always less than v_{vc} and the titer of the liquid-vapor mixture in the valve narrowest section depends on the upstream temperature and the operating Δp, so titer increases as these two parameters increase.

If the point representing the state of the fluid downstream lies inside the parabola, the product generated by throttling is a bi-phase fluid, i.e. a liquid in the presence of its own vapor.

Vaporization has already begun upstream of the valve narrowest section when the fluid crosses the limit curve. Valves having a recovery factor of $F = 1$ definitely operate in the flashing since volume continually and rapidly increases. The specific volume of point 2 is greater than in the valve narrowest section and much greater than that of state 1. In addition, it undergoes a sudden increase as it crosses the limit curve. Fluid temperature increases slowly at first (from point 1 to the limit curve) and after that rapidly increase up to the valve narrowest section value, which is retained even at outlet.

The titer of the mixture, as well as its specific volume, increases from the limit curve to the final point 2. For $F < 1$, the valve operates in flashing or cavitations, depending on whether the transformation from the valve narrowest section to final point 2 is above (or at least tangent to) the iso-titer curve intersecting 2, or else results with decreasing titer.

In flashing, the specific volumes, temperatures and titers progress as described above, whereas, in cavitations, temperature is lowest in the valve narrowest section, while specific volume and titer reach maximum values.

A low titer bi-phase fluid exists when point 1, representing the upstream physical state, is close to the lower limit curve.

The considerations expressed in the foregoing paragraph refer to low titer bi-phase fluids as well, but when the Δp generated titer in the valve narrowest section is equal to or greater than 0.5, cavitations is impossible and the valve operates in flashing.

A mixture whose titer is above 0.5 is classified as a high titer bi-phase fluid. The considerations of the preceding two paragraphs hold true in this case, too. However, it should be noted that in all cases the occurrence of cavitations may be excluded.

9 Conclusion

This paper analyzes the generation of internal entropy in the throttling process that takes place in the control valves. This type of irreversibility is defined to be internal irreversibility and occurs over the thermodynamic processes characterized by: friction between the working agent and the physical components of thermal machines, friction between the layers of heat, turbulence and homogenization in the agent that participates in the transformation of energy from one form to another.

All of thermodynamic processes are entropy generators but there are processes with such a high level of irreversibility so that couldn’t be ignored. That is why is so important to provide a feel for what causes entropy generation and to identify those system components that contribute the most to the overall irreversibility of the thermodynamic system. One of the processes with the highest level of entropy generation is flow with friction in various ducts and flow networks such as control valves.

So, this paper analysis pressure drop in different working conditions of valves. Also, for each analyzed situation are identified the possibilities to reduce the pressure drop and to rise the system energy efficiency through energy saving.

In the absence of friction (reversible transformation), the final state would be represented by point 1” (figure 3) and the fluid would accumulate all expansion work in the form of kinetic energy. In actual practice, however, since friction heat is present, the fluid is changing its density so that has a specific volume corresponding to that at point 2”. During 1-2” process the entropy increases with ΔS even though no heat exchanges with the outside occur. Transformation is thus adiabatic, and not isentropic. Shown on the entropic plane (T-S), it may be expressed as a polytropic curve passing through initial state 1 and final state 2” [11].

Downstream p_o pressures being equal, the increase in upstream pressure lowers the valve narrowest section pressure. Thus, a liquid throttled so that its physical condition upon reaching the valve narrowest section corresponds to conditions at the lower limit curve will start cavitations process from small p_i increases.

On the other hand, even small upstream pressure reductions can serve to sidestep the danger of critical operation and cavitation is avoided.

The considerations expressed in this paper refer to low titer bi-phase fluids as well, but when the Δp generated titer in the valve narrowest section is equal to or greater than 0.5, cavitations is impossible and the valve operates in flashing.

A mixture whose titer is above 0.5 is classified as a high titer bi-phase fluid. The considerations of the preceding two paragraphs hold true in this case, too. However, it should be noted that in all cases the occurrence of cavitations may be excluded.

References

[1] W.F. Hughes, *Fluid Dynamics*. – New York, Schaum’s Series, McGraw-Hill, 156-199,

[2] V. Marinoiu, I. Poschina, M. Stoica, *Robinete de reglare*.- Bucuresti, Editura tehnica, 203-229 2018

[3] O.P. Lovett Jr., *History of Control Valve Sizing*, First ISA Final Control Elements Symposium, May 14-16 Wilmington, Delaware, 2000

[4] R.P. Benedict, *Generalized Contraction Coefficients of an Orifice for Subsonic and Supercritical Flows*, Trans. ASME, J Basic Eng, 99-120, June, 1991

[5] I. Diaconescu, *Exergetic Analysis of Recovery Energy Process*, Romanian Technical Science Academy MOCM, no.14, vol.2, 2008, 77-71

[6] I. Diaconescu, *Thermodynamics nad Thermic Machines- Applications*, Ceprohart Publishing House, 1999, 98-121

[7] ISA *Handbook of control valves*, Instrument Society of America, Pittsburg, 1991, 21-87

[8]] I. Diaconescu, L.Tomulescu *Control Valves’ Thermodynamic Process Analysis* - Proceedings of the 3rd International Conference of Ph.D. Students, University of Mickolc, Hungary, Engineering Science, vol. 1, 2001,104-108

[9] O.P. Lovett Jr. *History of Control Valve Sizing* First ISA Final Control Elements Symposium, May 14-16 Wilmington, Delaware, 1997

[10] ***, *Control Valve Handbook*, Industrie Grafiche Casbot-Samarate, 1980

[11] Yousef Haseli, *Entropy Analysis in Thermal Engineering Systems* – Elsevier Inc. All rights reserved, ISBN 978-0-12-819168-2, 2020, pg.45-54

[12] Ioana Diaconescu, *Analysis of irreversible thermodynamic processes from control valves*, Proceedings of the 3rd WSEAS Int. Conf. on ENERGY PLANNING, ENERGY SAVING, ENVIRONMENTAL EDUCATION, 2009

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The author contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

The research in this manuscript is supported by “Dunarea de Jos” University of Galati.

Conflicts of Interest

The author has no conflicts of interest to declare that are relevant to the content of this article.

Creative Commons Attribution License 4.0 (Attribution 4.0 International, CC BY 4.0)