MEASURING A DISCHARGE COEFFICIENT OF AN ORIFICE FOR AN UNSTEADY COMPRESSIBLE FLOW

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There are many applications where a compressible gas flows through an orifice or a nozzle. This complex process has been examined for long time. Nevertheless current one or two dimensional mathematic and semi-empirical theories that predict a flow of a compressible gas through an orifice during an unsteady discharge from a vessel are only partially successful. It is impossible to treat all factors that might affect such a discharge. An experimental examination of a compressible gas flow through an orifice is still important part for evaluation and prediction of a discharge coefficient. This paper brings an idea for setup an apparatus on which a broad range of properties of an orifice can be tested. Several groups of properties were tested on different types of orifices and the results are presented.

Key words: discharge coefficient, compressible flow, unsteady flow, discharge from a vessel

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1. Introduction

A flow of a gas through an orifice can be characterized as steady or unsteady by mass flow rate through the orifice. If mass flow rate is constant during the examined process then flow is steady.

There are many applications where a gas flows through an orifice or a nozzle. One of the applications is a discharge of a gas from a vessel through an orifice. The discharge is treated as complex process that is characterized by properties of the gas, flow regime, properties of the orifice, properties of the vessel and properties of surrounding space. From a practical approach this complex system of properties could be simplified to one coefficient that could characterize difference between real and theoretic discharge. The discharge coefficient is usually treated as a parameter of an orifice that affects the area of the orifice for further computation [1].

It is impossible to treat all the factors that might influence practical discharge process. Even for relatively simple case of steady flow through an orifice several mathematical and semi-empirical solutions were obtained for well-defined sharp-edged orifices [2-4].

Discharge process is influenced even by shape and width of the orifice as stated before. Consequently even quality and shape of the upstream edge of the orifice has some influence on the discharge coefficient [5-7].

Thermodynamic parameters of the gas inside vessel are changing during the discharge process. The discharge process then does not depend only on thermodynamic properties in any instant but even on history of the discharge as stated in [8].

Temperature of the gas in the vessel during the discharge from the vessel is bounded on one side by temperature computed from adiabatic expansion and on the other side by the constant temperature of the gas at the beginning of the discharge process. In addition, thermal conditions in the vessel are changed not only by discharge process itself but even by heat transfer from space surrounding the vessel. For long term discharges this could be major influence that affects temperature of the vessel wall but even thermodynamic properties of the gas in the vessel at any instant of the process [9].

Consequently computation of the heat transfer from the surrounding space into the gas in the vessel is not a trivial problem. In this case convection is the main heat transfer process. Due to dynamic changes of the temperature of the gas inside the vessel the heat transfer is unsteady. For larger vessels natural convection takes main role during heat transfer and problem of boundary layer must be solved. The natural convection causes movement of gas layers inside the vessel so the temperature gradient in the gas changes not only with the time but even with the position in the vessel [10-12].

In this paper we propose measurements of discharge coefficient for several types of orifices with different shapes and other properties. In addition we have measured special type of orifices that extends measuring of two dimensional orifices to orifices with a three dimensional lift that can be found for example during pipeline accidents. We use a theoretic approach to determine temperature of a gas inside a vessel during a discharge process.

2. Experimental part

2.1. Theory

Suppose a vessel of a volume V [m^3] full of a gas characterized by a molar weight M [$kg.mol^{-1}$] and an isentropic coefficient κ [-]. Thermodynamic state of the gas is defined by a thermodynamic temperature T [K] and an absolute pressure P [Pa]. Properties of the gas inside the vessel are without subscript.

Space that is surrounding the vessel is filled by air with temperature T_{atm} and absolute pressure P_{atm}. Properties of the surrounding gas have subscript *atm*.

Let us define critical pressure ratio β [-]

$$\beta = \frac{P_{crit}}{P_{atm}} = \left(\frac{\kappa+1}{2}\right)^{\frac{\kappa}{\kappa-1}} \quad (1)$$

There is an orifice with an area S [m^2] connected to a vessel. When a gas is flowing through the orifice then a mass flow rate of the gas is

$$\dot{m} = G_{theor} S \tag{2}$$

where

$\dot{m}$ [kg s^{-1}] is a mass flow rate,

G_{theor} [kg.m^{-2}.s^{-1}] is a theoretic density of a mass flow rate and

S [m^2] is an area of the orifice.

Suppose that following properties are constant during the experiment:

- the temperature of air surrounding the vessel,
- the pressure of the air surrounding the vessel,
- the volume of the vessel and
- the molar weight of the gas in the vessel.

Influence of compressibility is omitted for our experiment and compressibility is treated as equal to one.

From thermodynamic analysis of the adiabatic flow we get equation for theoretical density of mass flow rate for adiabatic flow at any instant as

$$G_{teor}(t) = P_{atm}^{1/\kappa} P(t)^{(\kappa-1)/\kappa} \cdot \sqrt{2\frac{\kappa}{\kappa-1}\frac{M}{RT(t)}\left(1-\left(\frac{P_{atm}}{P(t)}\right)^{\frac{\kappa-1}{\kappa}}\right)} \tag{3}$$

when $\frac{P}{P_{atm}} < \beta$ and

$$G_{teor}(t) = P(t)\sqrt{\frac{M}{RT(t)}\kappa\left(\frac{2}{\kappa+1}\right)^{\frac{\kappa+1}{\kappa-1}}} \tag{4}$$

otherwise.

R [J.mol^{-1}.K^{-1}] is the universal gas constant equals to R=8.314 J.mol^{-1}.K^{-1}.

The mass in the vessel at any instant can be calculated from the state equation of the ideal gas

$$m(t) = \frac{P(t)VM}{RT(t)} \tag{5}$$

where V [m^3] is a volume of a vessel.

As a consequence of equation 2 and 5 we get an experimental density of a mass flow rate for measured values P(t) and T(t)

$$G_{exp}(t) = \dot{m}(t)S \tag{6}$$

Consequently a discharge coefficient α [-] is defined by

$$\alpha(t) = \frac{G_{\exp}(t)}{G_{theor}(t)} \tag{7}$$

2.2. Orifices

For the purpose of our experiment we developed and tested several types of orifices. They differ in shape, area and thickness to test broad range of parameters during experiments.

We prepared three-dimensional orifices for testing. Model of such orifice is in Figure 1. We called this type of orifices as *lifted*. The orifice consists of a two-dimensional orifice and a three-dimensional lifted flap, which may change effective area of the orifice and consequently discharge coefficient. Area of the lifted orifice, which is used for calculation, is the free area of the two-dimensional part of the orifice.

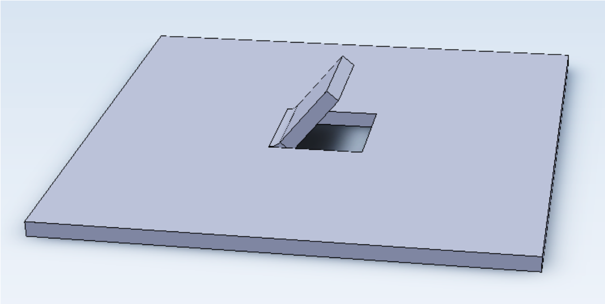

Figure 1 Model of a lifted orifice

Tab. 1 Properties of tested orifices

Label	Shape	S [mm^2]	Thickness [mm]	Angle of lift [°]
1_1	Circular	3.27	0.6	-
1_2	Circular	7.79	0.6	-
1_3	Circular	15.34	0.6	-
1_4	Circular	28.27	0.6	-
1_5	Circular	62.77	0.6	-
1_6	Circular	110.47	0.6	-
1_7	Circular	260.16	0.6	-
2_1	Circular	3.70	10.0	-
2_2	Circular	7.40	10.0	-
2_3	Circular	15.00	10.0	-
2_4	Circular	26.79	10.0	-
2_5	Circular	64.33	10.0	-
2_6	Circular	111.59	10.0	-
2_7	Circular	262.73	10.0	-
S1	Narrow rectangular slot	5.16	1.6	-
S2	Narrow rectangular slot	18.95	1.6	-
C1.1	Square	28.62	1.6	-
C2.1	Square	113.42	1.6	-
C2.1	Square	93.72	1.6	33
C2.3	Square	84.14	1.6	52
T1.1	Triangular	22.45	1.6	-
T2.1	Triangular	99.39	1.6	-
T2.2	Triangular	90.90	1.6	33
T2.3	Triangular	94.69	1.6	43

2.3. Apparatus

We built an apparatus for measuring a discharge coefficient during an unsteady discharge. The apparatus consists of a main pressure vessel, a flange for a tested orifice and a pressure and temperature sensor. Volume of the main pressure vessel is 0.16 m^3. Maximum operating overpressure is 1 MPa.

We use naked thermocouples for measuring temperature inside and outside of the vessel. Thermocouples are calibrated online by Pt100 sensor at the beginning of each experiment.

Gas is supplied from a high pressure cylinder in order to guarantee the same quality of the gas during experiments. Because temperature drops subzero rapidly during experiments low humidity of supplied gas is also very important.

Data from temperature and pressure sensors are acquired via Advantech 16 bit AD convertor and with timestamp synchronously logged by computer.

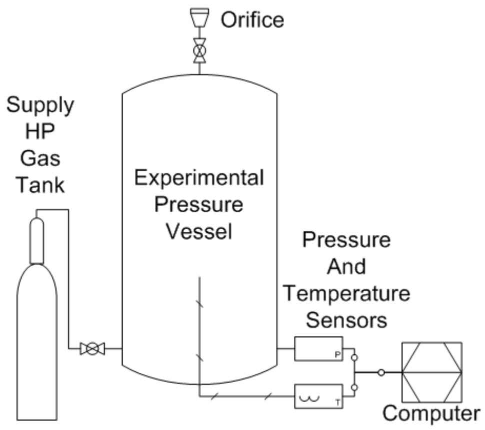

Figure 2 Experimental apparatus

2.4. Setup of an experiment

A tested orifice was attached and sealed to the outflow flange. The main pressure vessel was filled by air from high pressure cylinder up to overpressure about 0.85 MPa. Because pressure was reduced from high-pressure in the HP gas cylinder to medium pressure inside the vessel, temperature of the filled gas was lower than surrounding temperature.

After an hour both temperatures equalized. Then overpressure inside the vessel was examined and finely adjusted to 0.85 MPa. Surrounding barometric pressure was measured by an independent instrument and logged. After computer program for data logging was started, the outflow valve was opened and the discharge process began.

3. Results

Even though we use naked thermocouples for measuring of temperature, they are only in industry-level quality and their time constant is too long for measuring fast changes of the gas temperature inside the vessel during some of our experiments. We implemented Landram's equation system to compute temperature inside the vessel [10]. The mathematical model of the temperature inside the vessel was adjusted to correspond with experimental data.

Results of our experiments are grouped by dominating parameters of the tested orifices – shape and area.

At first we tested circular orifices with different areas. Results for thin circular orifices are shown in Figure 3 and for thick circular orifices in Figure 4. For thin orifices the discharge coefficient decreases rapidly with decreasing pressure in the vessel in contrast to thick orifices, which discharge coefficient is more stable during the discharge. The discharge coefficient does not depend heavily on the area of the orifice in both "families" of orifices. Orifices with the smallest area are the only exception.

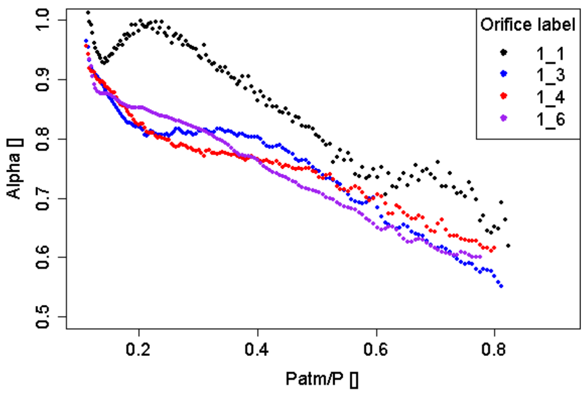

Figure 3 Dependency of the discharge coefficient α on P_{atm}/P for a subset of thin circular orifices

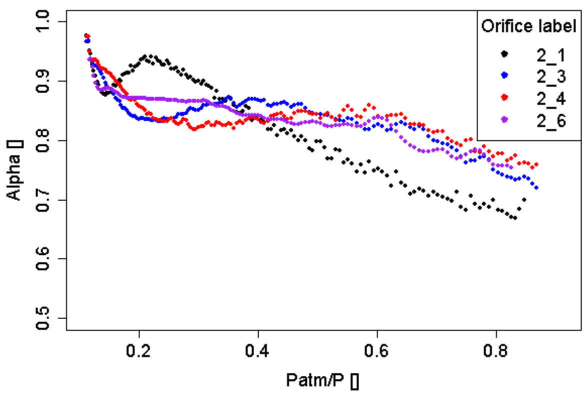

Figure 4 Dependency of the discharge coefficient α on P_{atm}/P for a subset of thick circular orifices

Discharge coefficients for square orifices are shown in Figure 5 together with results for thin circular orifices that have similar area. Orifice C1.1 is comparable to orifice 1_4 and C2.1 to 1_6. Graph shows that discharge coefficient of circular and square orifices with similar areas are closely related, even though there might be differences for orifices with bigger areas.

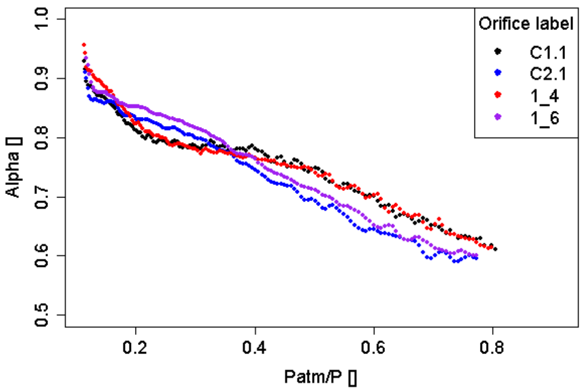

Figure 5 Dependency of the discharge coefficient α on P_{atm}/P for square orifices and thin circular orifices with comparable area

Discharge coefficients of narrow rectangular slots are much higher than discharge coefficients for comparable circular orifices (Fig 6). The same phenomenon can be more clearly observed for triangular orifices (Fig 7). But it seems that the effect decreases with increasing area of the orifice.

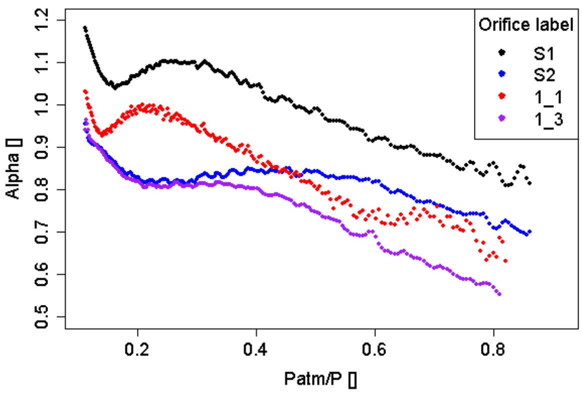

Figure 6 Dependency of the discharge coefficient α on P_{atm}/P for narrow rectangular slots and thin circular orifices with comparable area

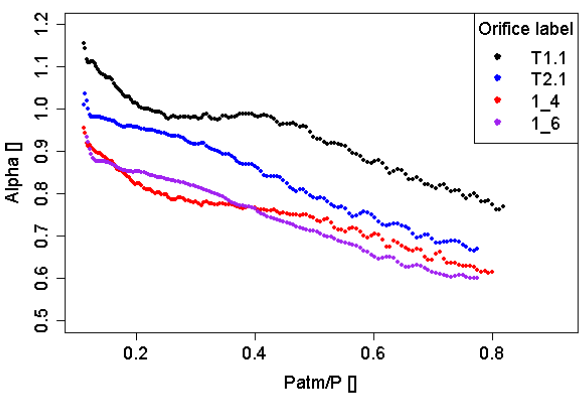

Figure 7 Dependency of the discharge coefficient α on P_{atm}/P for triangular orifices and thin circular orifices with comparable area

Results for orifices with a lift are shown in Figure 8 for square orifices and in Figure 9 for triangular orifices. All lifted orifices were tested on both sides. So the results show discharge coefficients for upstream position of the lift –label *Up* and for downstream position of the lift – label *Down*. Upstream position of the orifice means that the lifted part is oriented against the flow.

As is clearly visible from Figures 8 and 9 the position and the angle of the lift significantly affect value of the discharge coefficient. Smaller angle of the lift reduces the discharge coefficient comparing to the discharge coefficient of the fully opened two-dimensional orifice of the same shape and area. In contrast the angle of the lifted part that is greater than some value can increase discharge coefficient above the coefficient of flat square shaped orifice with the same area. For the triangular lifted orifices the discharge coefficients are much lower than the discharge coefficient of the flat triangular orifice with the same area. But higher lift angles of tested square and triangle orifices are not the same, so the threshold angle of the phenomenon mentioned above for square orifices may still exist even for triangle orifices.

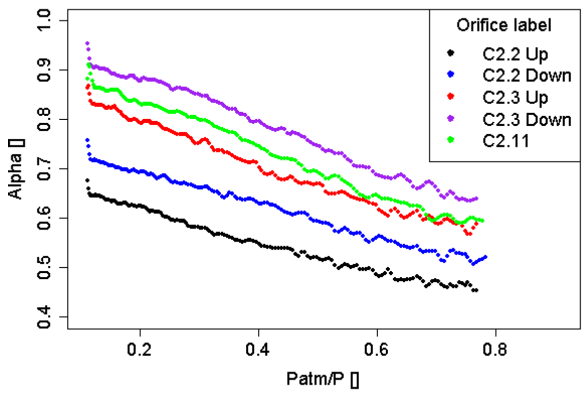

Figure 8 Dependency of the discharge coefficient α on P_{atm}/P for square orifices with a lift positioned upstream and downstream and flat square orifice with comparable area

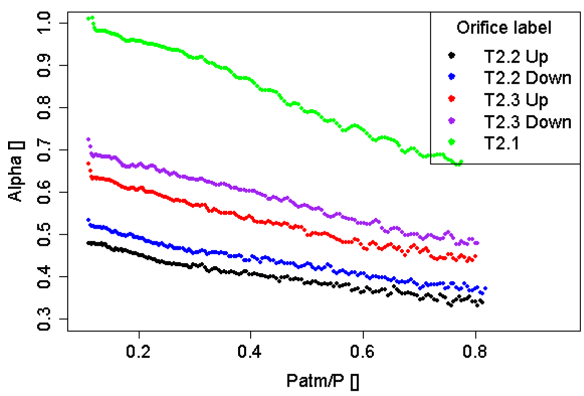

Figure 9 Dependency of the discharge coefficient α on P_{atm}/P for triangular orifices with a lift positioned upstream and downstream and flat triangular orifice with comparable area

Upstream and downstream position of the lift affects the discharge coefficient of the orifice. The discharge coefficient of the same lifted orifice is bigger in downstream position then in upstream position. Same effect was observed for both square and triangle orifices.

Deeper investigation of the lift angle effect on the discharge coefficient will be the main task for the further research.

4. Conclusion

In this paper we proposed measurements of the discharge coefficient for several types of orifices with different shapes and other properties. In addition we measured special type of orifices that extends measuring of discharge coefficient of the two-dimensional orifices to the measuring of the discharge coefficient of the orifices with a three-dimensional lift. They can be found on ruptured pipelines during pipeline accidents caused by puncturing the pipeline from outer side. We used Landram's theoretic approach to determine the temperature of the gas inside the vessel during measured discharge processes.

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