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FLOW CONDITIONS DURING BLOW-OFF OF GAS PIPELINE

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Abstract. The authors worked out a computational process and software for calculating the working conditions of blow-off systems at technological stations of gas pipelines. One part of the investigated system is the closed gas pipeline section, the other is the blow-off pipe provided with a control valve. To create the model they analysed the blow-off process, on the basis of which the simplifying assumptions were determined. The calculation model gives unsteady values of pressure, temperature and the gas flow at chosen points of the system. In the second part of the article the authors demonstrate the application of the computational algorithm by solving an example.

Keywords: Pipeline depressurising, venting system, blow-off pipe, Fanno flow, energy equation, subsonic flow.

1. Introduction

The high-speed pipe flow with friction has been investigated first by Frössel [1]. Pressure distribution charts were obtained both for subsonic and supersonic flow. Prandtl [2] elaborated the first mechanical model in which the friction factor depends not only on the Reynolds number but also on the Mach number. Shapiro, Hawthorne and Edelman [3] gave a complex mechanical and thermodynamical analysis of the problem. Their results are provided in tabulated form for numerical solutions. Landau and Lifsic [4] investigated the high speed gas flow through an adiabatic pipe. Their sophisticated analysis has mainly academic interest from the point of view of theoretical physics. Tihanyi, Bobok and Bódi [5] provided an analytical solution oriented to applications in natural gas engineering.

2. Blow-off system

The blow-off system is a complementary part of disconnecting or technological stations, which serves for depressurising pipeline sections. During blow-off, the gas in the pipeline section which is closed at both ends is discharged through a special pipeline system, and throughout the process the own pressure energy of the gases is used. Because of environmental regulations, the discharged gas is generally burnt, therefore the process is also called flaring of gas. Gas pipeline blow-off systems are infrequently in operation, while refinery and gasworks flares are continuously being burnt. That is why their sizes and arrangements are different.

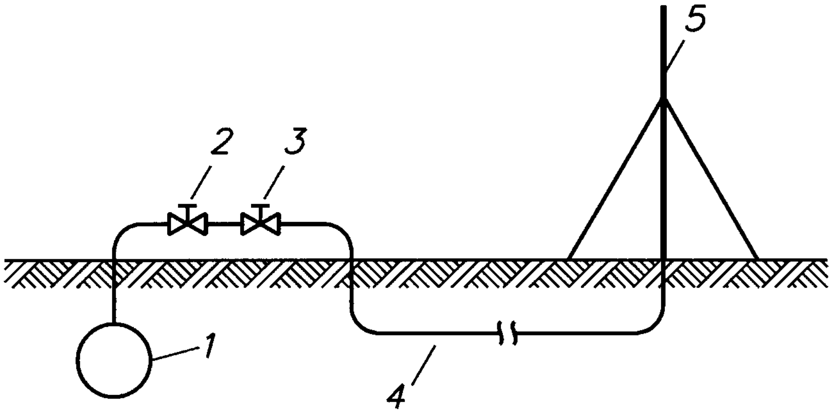

Figure 1. Arrengement of the blow-off system. 1 closed section of the main pipeline, 2 control valve, 3 gate valve, 4 blow-off pipe, 5 stack

For technological and safety reasons, gas outflow can be controlled by reducing the cross-section of the discharge area of the stack. Regulations in Hungary allow Mach number 0.2 under normal circumstances, while 0.6-0.8 is allowed in an emergency. The usual technological arrangement of blow-off systems at pipeline disconnecting stations can be seen in Figure 1.

At the entrance of the blow-off pipe, a control valve and a gate valve are built in. The volume of gas escaping from the closed pipeline section can be controlled manually by means of a control valve.

3. Pressure and temperature changes in the closed pipeline section

When calculating the blow-off process, the examined system can be clearly divided into two parts. One part is the closed pipeline section which has to be depressurised and can be regarded as a “reservoir”. The other is the blow-off pipe, the cross-section of which is either fixed or adjustable. At the “reservoir” of the whole system, changes in pressure and temperature have to be controlled by assumptional blow-off gas flow. For the part including the blow-off pipe and the control valve, the gas flow rate must be calculated considering hydraulic assumptions for the initial and final points and the control mode. The calculation for the complete system can only be done using approximation methods.

The pressure change in the closed pipeline section can be calculated applying the perfect gas law:

$$\frac{p_1}{z_1} - \frac{p_2}{z_2} = \frac{RT}{M_g V_{pipe}} \Delta m \, . \tag{3.1}$$

The formula gives the pressure change when altering the amount of gas in volume V_{pipe} with a mass of Δm. Subscript 1 refers to the initial, while subscript 2 refers to the final conditions. Since the compressibility factor depends on pressure and temperature, the equation can only be solved by successive approximation.

As pressure and temperature in the closed pipeline section change simultaneously, different assumptions can be used as starting points

a) the expansion is isentropic, only gas temperature changes,
b) the expansion is polytropic, only gas temperature changes,
c) during expansion gas temperature and the temperature of the steel pipe change in the same measure, but no heat exchange occurs between the system and its environment,
d) during expansion gas temperature in the latter two cases, pipe wall temperature and also the heat content of the gas in the pipeline section are to be taken into consideration.

Supposing environmental heat exchange between the gas and its surrounding, we have to consider heat convection between the gas flow and the soil in area A of the pipe. Choosing heat transmission coefficient $k = 0$, the effect of the latter can be disregarded. The formula to calculate the temperature of the gas in the closed pipeline section regarded as a “reservoir” derived from the balance of heat is the following:

$$T_{i+1} = \frac{c_s m_s T_i + c_g m_g T_i + kA\Delta\tau T_t}{c_s m_s + c_g m_g + kA\Delta\tau T_t} \tag{3.2}$$

The specific heat of the gas can be calculated from the equation of state at the actual pressure and temperature; the specific heat of the steel can be determined by extrapolating chart values. The mass of gas is the actual value in the pipeline section at the examined time; the mass of steel is to be given as basic data. Similarly, the heat transmission coefficient is to be given as input data, the heat convection area is to be calculated from pipeline section parameters. Time step $\Delta\tau$ depends on the calculation algorithm. Temperature can be determined from formula (3.2) by successive approximation.

Comparing the results of calculations on the basis of assumptions a/ ... d/ with blow-off experiences, it seems reasonable to choose the boundary area not on the internal but on the external surface, at the passive insulating layer. It is because the mass and heat contents of the pipeline are multiples of the mass and heat contents of the gas inside it, that the balancing effect of the mass of the steel pipe cannot be neglected. For example, the specific mass of a pipeline with 600 mm nominal diameter is 164 kg/m, while the mass of the gas at a pressure of 50 bar in a 1 m pipeline section is only 10.7 kg. Since the gas is in direct contact with the inner wall of the pipeline, thermal equilibrium can take place in a short period of time. In the calculation model of formula (3.2) the temperature of the pipeline and that of the gas inside it change in the same extent.

Another question in connection with the "pressure vessel or reservoir" is whether a significant gas flow develops in the pipeline section during the blow-off process, which would cause a non-negligible pressure difference. Considering that the blow-off process is not for its own sake but is the preparatory phase of maintenance, we have to aim at minimising the process time. If there is no excluding factor, the blow-off process is carried out at both ends of the pipeline at the same time. In this case pressure will change evenly along the pipeline section and no significant gas flow will develop. On this basis, at all the points along the closed pipeline section pressure should be taken as constant.

4. Gas flow in the blow-off system

In the blow-off system linked with the "reservoir", i.e. the pipeline section, a complicated form of flow develops. Pressure and temperature at the initial point of the blow-off system are derived from the "main line section model". The first element of the blow-off system is a short pipe section which links the main pipeline section with the control valve. In this pipe section pressure is still high and flow velocity is relatively low. The control valve is joined with the branch pipe, with the help of which pressure can be reduced, therefore the gas flow can be controlled. Throttling control can be regarded as an isoenthalpic change of state. The gas flow developing at the nozzle or at the throttle is determined by the back pressure at the outflow end of the nozzle. In the pipe section following the nozzle, i.e. the real blow-off pipe, the pressure of the gas further decreases but its velocity increases. Depending on the gas flow and the length of the blow-off pipe, a critical velocity can develop at the outflow end. During the blow-off process the flowing gas expands, its pressure and temperature decrease point by point.

The physical model and the calculation formulas describing high-velocity gas flows developing in blow-off systems are different from those describing flowing conditions in normal pipeline operation. The pressure loss is increased by friction and very fast expansion, which mostly depends on the Mach-number [6]. For the purpose of practical calculations, the most important flow parameters are given in charts according to the Mach-number [7]. In the case of high-velocity gas flows there is a significant difference between the stagnation pressure p_0 and the static (or free-stream) value p_s. Similarly the stagnation temperature T_0 is higher than static T_s, because the sensing element is brought to rest. Thus the kinetic energy of the gas is converted into enthalpy, which results in the higher temperature reading [8]. Therefore the stagnation pressure and temperature may be written as functions of the Mach-number:

$$p_s = \frac{p_0}{\left(1 + \frac{\kappa-1}{2} M^2\right)^{\frac{\kappa}{\kappa-1}}} \tag{4.1}$$

$$T_s = \frac{T_0}{\left(1 + \frac{\kappa-1}{2} M^2\right)} \,. \tag{4.2}$$

Because of the extremely high velocity of the gas flow moving along the blow-off pipe, the environmental heat exchange is negligible. Thus, from the viewpoint of the gas the system behaves as if it was heat-insulated [9]. At the same time, the energy loss due to friction must be taken into consideration for actual pipelines. The gas flow developing under such conditions is called Fanno-flow. To describe the process, the differential form of the mechanical balance of energy for high-velocity, frictional gas flows developing in heat-insulated pipes can be applied:

$$v\mathrm{d}v + \frac{\mathrm{d}p}{\rho} + \frac{\mathrm{d}p^{'}}{\rho} = 0\ . \tag{4.3}$$

In the equation dp' is the frictional pressure loss for length element dl. The Weissbach-equation can be applied to the length element:

$$\mathrm{d}p' = f_D \frac{\mathrm{d}l}{D}\rho\frac{v^2}{2} \tag{4.4}$$

where f_D is the friction factor, and D is the pipe diameter. As the gas expands the flow velocity and the friction factor change point by point. The pressure change for length element dl is:

$$\mathrm{d}p = -\rho v \mathrm{d}v - \frac{f_D \rho v^2}{2D}\mathrm{d}l\ . \tag{4.5}$$

From the continuity and state equations the following correlation can be derived for the pressure, velocity and temperature:

$$\frac{\mathrm{d}p}{p} = -\frac{\mathrm{d}v}{v} + \frac{\mathrm{d}T}{T}\ . \tag{4.6}$$

Term dT/T can be determined by differentiating the equation for sonic speed:

$$2\frac{\mathrm{d}a}{a} = \frac{\mathrm{d}T}{T}\ . \tag{4.7}$$

Combining equations (4.6) and (4.7) yields:

$$\frac{\mathrm{d}p}{p} = -\frac{\mathrm{d}v}{v} + 2\frac{\mathrm{d}a}{a}\ . \tag{4.8}$$

When transforming the equations, we have to consider that

$$\frac{\rho}{p} = \frac{\kappa}{a^2}$$

where κ is the specific heat ratio. Finally we get the following differential equation:

$$2\frac{\mathrm{d}a}{a} - \frac{\mathrm{d}v}{v} = -\frac{\kappa f_D}{2D}\left(\frac{v}{a}\right)^2 \mathrm{d}l - \kappa\frac{v\mathrm{d}v}{a^2}\ . \tag{4.9}$$

From this equation we can see that the frictional loss coefficient for the length element $f_D dl/D$ depends only on flow velocity and sonic speed, and is independent of viscosity and surface roughness. If we consider that the ratio of flow velocity and sonic speed is the Mach number equation (4.9) can be reshaped:

$$f_D \frac{\mathrm{d}l}{D} = \frac{2\left(1 - M^2\right)\mathrm{d}M}{\kappa M^3 \left(\frac{\kappa-1}{2} M^2 + 1\right)} \,. \tag{4.10}$$

Integrating this equation between two given points of the pipeline we get a formula by means of which the change in the Mach number can be calculated between two points of the pipeline. The Mach number distribution along the pipeline can be determined by repeating the calculation steps [10]:

$$\frac{f_D L}{D} = \frac{1}{\kappa M_1^2} - \frac{1}{\kappa M_2^2} + \frac{\kappa+1}{2\kappa} \ln \frac{M_1^2}{M_2^2} \left[\frac{2 + (\kappa-1) M_2^2}{2 + (\kappa-1) M_1^2}\right] \,. \tag{4.11}$$

If Mach numbers are known at chosen points of the pipeline, pressure and temperature can be calculated using the following formulas:

$$\frac{p_{s2}}{p_{s1}} = \frac{M_1}{M_2} \left[\frac{2 + (\kappa-1) M_2^2}{2 + (\kappa-1) M_1^2}\right] \tag{4.12}$$

$$\frac{T_{s2}}{T_{s1}} = \frac{1 + \frac{\kappa-1}{2} M_1^2}{1 + \frac{\kappa-1}{2} M_2^2} \,. \tag{4.13}$$

Applying equations (4.11), (4.12) and (4.13), the flow conditions can be determined in the actual flare system [11].

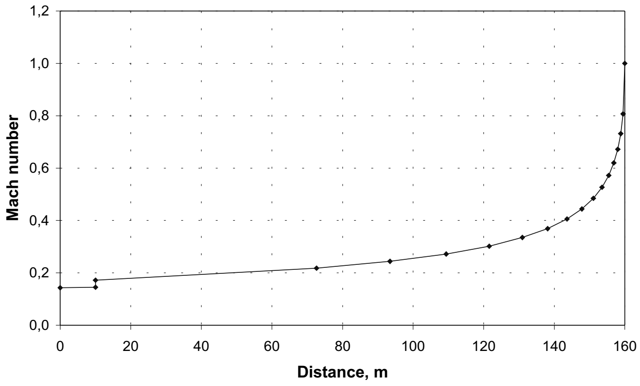

Figure 2. Changes in the Mach number according to distance

As an example let us see a blow-off system where the pipeline section to be venting and the control valve placed on the surface are connected by a 10 m long branch pipe, and the blow-off pipe. Following the control valve there is a 150 m long blow-off pipe, through which the gas flows into the environment. The blow-off pipe before and after the control valve is of 100 mm nominal diameter. In Figure 2 changes in the Mach number can be seen in the complete system. In the short pipe between the main line and the control valve, the Mach number is 0.14 in accordance with the blow-off gas flow rate, which barely changes along the pipe. Because of pressure decrease between the two sides of the control valve, the Mach number at the output point is 0.17. Because of the expansion, flow velocity in the blow-off pipe grows continuously and reaches the Mach number 1, i.e. critical flow velocity, at the outflow end.

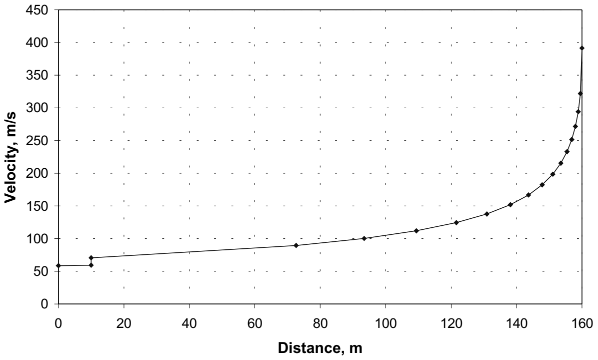

Figure 3. Changes in flow velocity according to distance

The changes in flow velocity are not linear along the blow-off pipe. In the section following the control valve, the velocity change is rather slow, the Mach number is only 0.5 at 10 metres before the outflow end. However, in the last 10 m section velocity changes extremely fast. The characteristic shape of the curve in Figure 2 has to be taken into consideration when dividing the blow-off pipe into sections, which means that the sections have to get shorter towards the outflow end. Figure 3 shows that the growth of flow velocity along the pipeline is similar to that of the Mach number. It is only moderate along nine tenths of the blow-off pipe but is powerful in the last one tenth.

Temperature of the gas flow changes as a result of adjustment and expansion. Figure 6 shows that temperature at the beginning point of the blow-off system is 2.4 ^{o}C, after adjustment it is 1.8 ^{o}C lower. There is significant cooling during the flare process at the outflow end where temperature reaches the lowest value -35 ^{o}C.

Figure 5 illustrates changes in pressure along the blow-off pipe. In the short pipeline section before the control valve, pressure decrease is only 0.3 bar because of low flow velocity. At the output point of the control valve pressure is 17.2 bars because pressure decreases by 3 bars during the control process. The pressure loss of 15.3 bars in the blow-off pipe is mainly due to the large gas flow. Eventually, pressure at the outflow end is 2 bars higher than environmental pressure.

Figure 6 illustrates the correlation between limiting conditions at the outflow end of the blow-off pipe and the developing gas flow rate in the case of a 100 mm nominal diameter pipeline. While the Mach number is below 1, pressure at the outflow end of

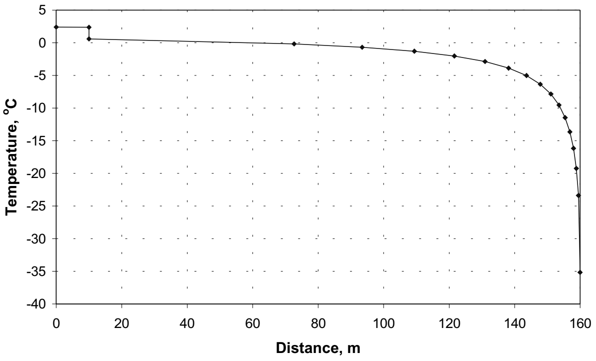

Figure 4. Changes in temperature according to distance

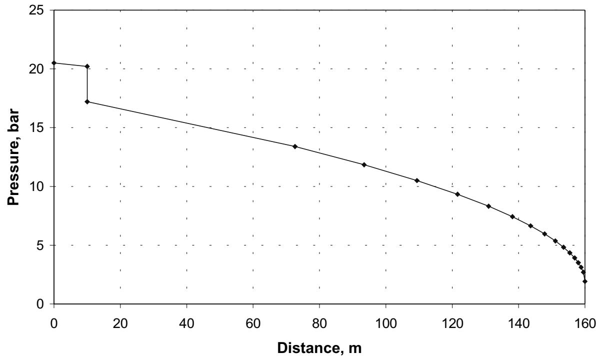

Figure 5. Changes in pressure according to distance

the blow-out pipe is equal to ambient pressure, i.e. there is no overpressure. Under this flow condition the outflow rate is proportional to the Mach number. If the critical outflow velocity is reached by increasing the flare gas flow, further increase can only be achieved by increasing density, and not velocity. Under this flow condition the pressure at the outflow end will exceed ambient pressure.

5. Practical application

The examined system is a 15 km long 600 mm nominal diameter pipeline section, in which the pressure at the beginning of the blow-off process is 25 bars, and (soil) temperature is 5 ^{o}C. The flare system consists of a 10 m long linking pipe, an adjusting valve and a 150 m long blow-off pipe with 100 mm nominal diameter.

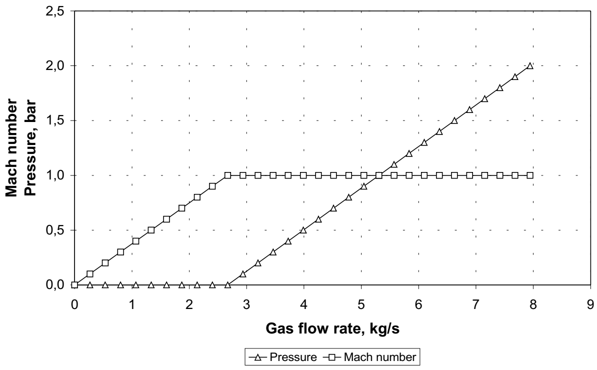

Figure 6. Outflow rate according to the Mach number and pressure

When processing computational results, subscript 1 always refers to the “reservoir”, i.e. the closed pipeline section, subscript 3 to the output point of the control valve and subscript 4 to the outflow end.

During the blow-off process different control methods can be implemented, which result in different flow conditions. Each control method also influences the venting time through the gas flow rate.

Figure 7 shows volumes of three different gas flows under different technical conditions:

- pressure difference at the control valve is a constant of 3 bars,
- the volume of the controlled gas flow is a constant of 5.73 kg/s,
- the Mach number at the outflow end is a constant of 0.8.

If the control valve allows, adjusting at constant pressure difference is chosen. The blow-off process can be carried out within a short period of time initially with large, then fast decreasing gas flow. At constant gas flow first large, then gradually decreasing throttling must be ensured on the control valve, and the process is to be finished with the control valve completely open. If the critical velocity is not reached, i.e. the Mach number is below 1, the gas flow in the first phase will be constant, then it will gradually decrease.

Controlling the blow-out process by given pressure difference the constant pressure decrease at the adjusting valve is 3 bars. Figure 8 shows that the flare process can be divided into three parts. The first phase lasts 2 hours 47 minutes, and constant throttling of 3 bars can be sustained between the two sides of the control valve. In this period pressure loss can be neglected in the short branch pipe linking the main pipeline section with the throttling valve, therefore “stagnation pressure” p_1 and the output pressure of the control valve decrease simultaneously. In the second period throttling must be gradually decreased, and finally in the third period after 3 hours 41 minutes the control valve has to be opened completely, and there is no need for adjusting.

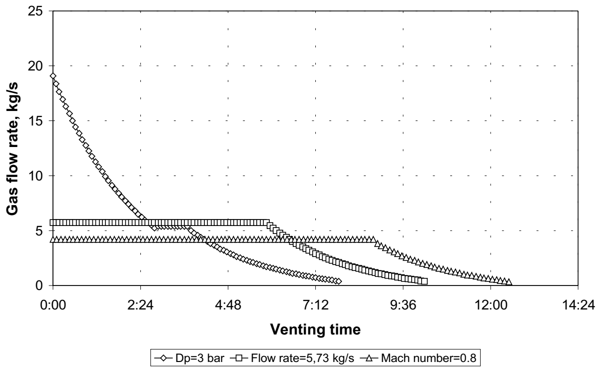

Figure 7. Comparing control methods

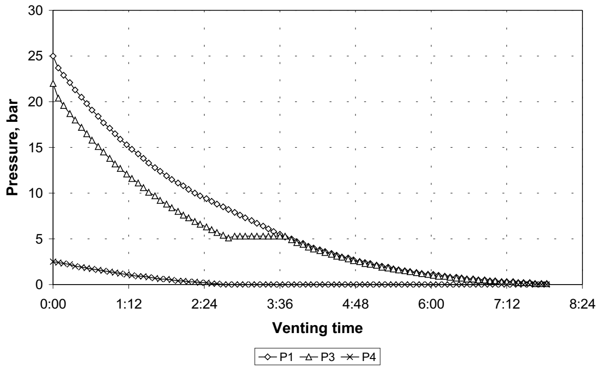

Figure 8. Pressure change versus time

In the first phase when pressures p_1 and p_3 decrease simultaneously, p_4 at the outflow cross-section is higher than the ambient pressure. After 2 hours 47 minutes, the Mach number 1 at the outflow end could only be kept by reducing throttling. In 3 hours 41 minutes throttling reaches zero, thus in the remaining venting time is carried out without throttling, with completely open control valve. The figure shows that stagnation pressure in the last phase decreases below 5 bars. The blow-off process is continued for 7 hours 50 minutes with gradually decreasing outflow. After 3 hours 41 minutes, i.e. in the last phase, pressure at the outflow cross section is equal to ambient pressure.

Figure 9 shows the temperature calculated throughout the process. Stagnation temperature T_1 in the first, intensive phase decreases from soil temperature of 5 ^{o}C to -0.8 ^{o}C, then in the next phase it increases due to surrounding heat convection. At the output point of the throttling valve temperature T_3 changes parallel with T_1 due to constant pressure difference. At the outflow point of the stack in the first phase, gas

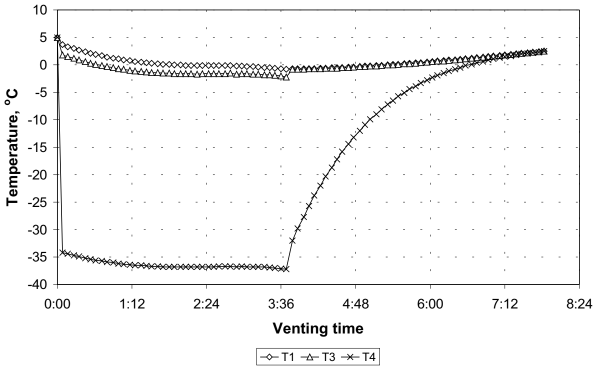

Figure 9. Change of temperature versus time

temperature T_4 becomes very low because there is a significant expansion when flow velocity reaches sonic speed. Later, as the outflow Mach number decreases, expansion becomes smaller along the pipe, thus outflow temperature gradually approaches temperature T_3 at the beginning point of the blow-off pipe.

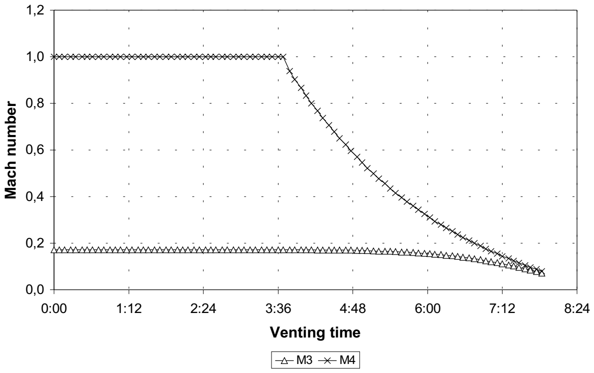

Figure 10. Changes in Mach number versus time

Figure 10 shows that gas velocity reaches sonic speed in the phase of throttling controlling when $\Delta p > 0$, i.e., Mach number M_4 at the outflow end is 1. In the last phase of blow-off without throttling M_4 decreases due to the gas flow decrease.

Mach number M_3 refers to the output point of the control valve. There are no breakpoints on the curve at the ends of the blow-off phases, which means that the transition between the different control methods is continuous. In the last phase of process, due to gradual gas flow decrease, the Mach number at the output point of the control valve decreases as well, and the two curves approach each other fast.

6. Conclusions

Blow-off systems are important complementary parts of gas transportation systems. Blow-off is generally needed when gas needs to be removed from a pipeline section. During the process a high-velocity gas flow develops, which shows a significant difference compared with change of state and form of flow under normal operation of gas transportation systems. It is reasonable to divide the system into two parts: the closed section of the main pipeline in which the gas volume continuously decreases; and a blow-off pipe provided with a control valve, through which the controlled gas flow is discharged into the environment.

Assumptions have to be examined for both parts of the system in order to get the best approach to the process taking place. The next step is to determine the mathematical model. Setting out from the calculation formulas, an algorithm can be created to be realized in software form.

With the help of the example presented in the article, the changes in the most characteristic parameters can be seen along the blow-off pipe and also their unsteady changes at chosen points of the system. So the reader can be convinced of not only the accuracy of the calculation process, but can also see the process under different adjusting conditions.

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