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A NEW MODEL FOR BLOW-OFF OF A GAS PIPELINE

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 gases' own pressure energy 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 arrangement are different.

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 the Mach-number 0.2 under normal circumstances, while 0.6-0.8 in 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 the control valve.

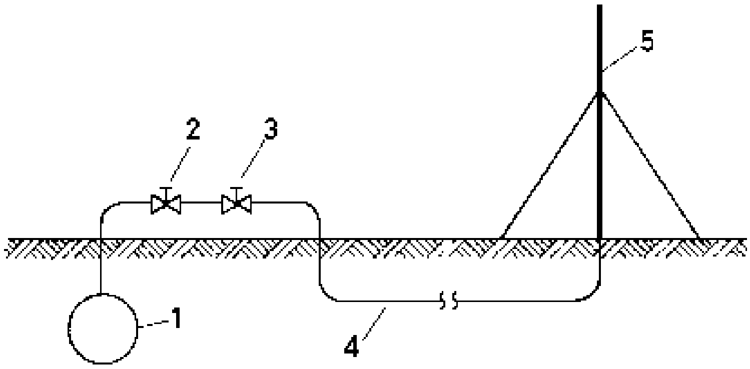

Fig. 1. Plan of the blow-off system.
1 closed section of the main pipeline, 2 control valve, 3 gate valve, 4 blow-off pipe, 5 stack

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 general gas law:

$$\frac{p_1}{z_1} - \frac{p_2}{z_2} = \frac{RT}{M_g V_{pipe}} \Delta m \,. \tag{1}$$

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 adiabatic, 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:

$$T_{i+1} = \frac{c_s m_s T_i + c_g m_g T_i + kA\Delta\tau T_t}{c_s m_s + c_g m_g + kA\Delta\tau T_t} \,. \tag{2}$$

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 Δτ depends on the calculation algorithm. Temperature can be determined from formula (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, therefore the balancing effect of the pipe's steel mass cannot be neglected. For example, the specific mass of a pipeline with 600 ND (24 in.) is 164 kg/m (110 lb/ft), while the mass of the gas at a pressure of 50 bar (725 psi) in a 1 m (3.3 ft) pipeline section is only 10.7 kg (23.6 lb). 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 (2) the temperature of the pipeline and that of 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 minimizing 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.

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 flowing 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 (Oswatitch et al., 1957). For the purpose of practical calculations, the most important flowing parameters are given in charts according to the Mach-number (Streeter, 1961). 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. Therefore the stagnation pressure and temperature may be written as functions of the Mach-number:

$$p_s = \frac{p_0}{\left[1+\frac{\kappa-1}{2}M^2\right]^{\frac{\kappa}{\kappa-1}}} \quad ; \tag{3}$$

$$T_s = \frac{T_0}{\left[1+\frac{\kappa-1}{2}M^2\right]} . \tag{4}$$

Because of the extremely high velocity of the gas flow moving along the blow-off pipe, the environmental heat exchange is actually negligible. Thus, from the viewpoint of the gas the system behaves as if it was heat-insulated (Liepmann et al., 1957). 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:

$$vdv+\frac{dp}{\rho}+\frac{dp'}{\rho}=0\,. \tag{5}$$

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

$$dp'=f_D\frac{dl}{D}\rho\frac{v^2}{2}\,, \tag{6}$$

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

$$dp=-\rho vdv-\frac{f_D\rho v^2}{2D}dl\,. \tag{7}$$

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

$$\frac{dp}{p}=-\frac{dv}{v}+\frac{dT}{T}\,. \tag{8}$$

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

$$2\frac{da}{a}=\frac{dT}{T}\,. \tag{9}$$

After displacement, the differential equation is the next:

$$\frac{dp}{p}=-\frac{dv}{v}+\frac{2da}{a}\;. \tag{10}$$

When transforming the equations, we have to consider that

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

In the end, we get the following differential equation:

$$2\frac{da}{a}-\frac{dv}{v}=-\frac{\kappa\cdot f_D}{2\cdot D}\left(\frac{v}{a}\right)^2dl-\kappa\frac{v\cdot dv}{a^2}\,. \tag{11}$$

From the equation we can see that the frictional loss coefficient for the length element $f_D$dl/D only depends on flow velocity and sonic speed, and is independent of viscosity and roughness. If we consider that the ratio of flow velocity and sonic speed is the Mach-number, we have equation (11) in another form:

$$f_D\frac{dl}{D}=\frac{2\cdot\left(1-M^2\right)\cdot dM}{\kappa\cdot M^3\cdot\left(\frac{\kappa-1}{2}M^2+1\right)}\;. \tag{12}$$

Integrating the equation between two given points of the pipeline we get a formula with the help 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 (Coulter, 1984):

$$\frac{f_DL}{D}=\frac{1}{\kappa M_1^2}-\frac{1}{\kappa M_2^2}+\frac{\kappa+1}{2\kappa}ln\frac{M_1^2}{M_2^2}\left[\frac{2+\left(\kappa-1\right)}{\;}\right]\;. \tag{13}$$

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

$$\frac{p_{s2}}{p_{s1}}=\frac{M_1}{M_2}\sqrt{\frac{2+\left(\kappa-1\right)M_1^2}{2+\left(\kappa-1\right)M_2^2}}\;; \tag{14}$$

$$\frac{T_{s2}}{T_{s1}} = \frac{1 + \frac{\kappa - 1}{2} M_1^2}{1 + \frac{\kappa - 1}{2} M_2^2} . \tag{15}$$

Applying formulas (13), (14) and (15), the flowing conditions can be determined in the actual flare system.

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 (33 ft) long branch pipe, and the blow-off pipe. Following the control valve there is 150 m (492 ft) 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 ND (4 in.). 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.

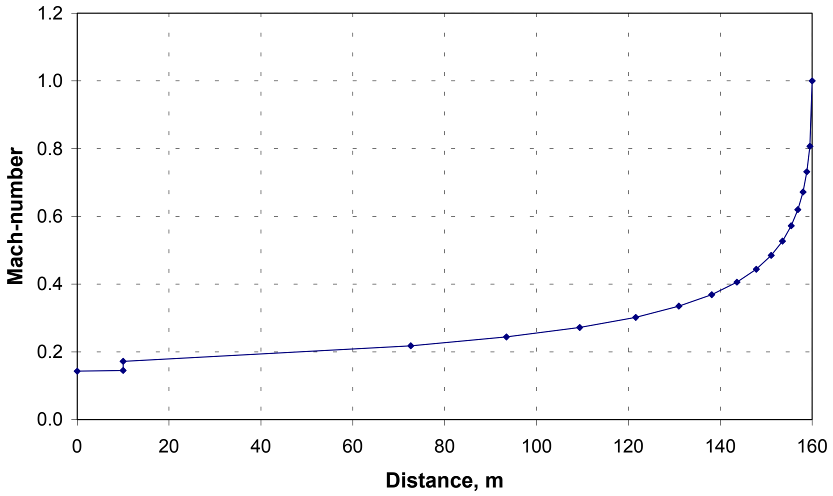

Fig. 2. Changes in Mach-number with distance

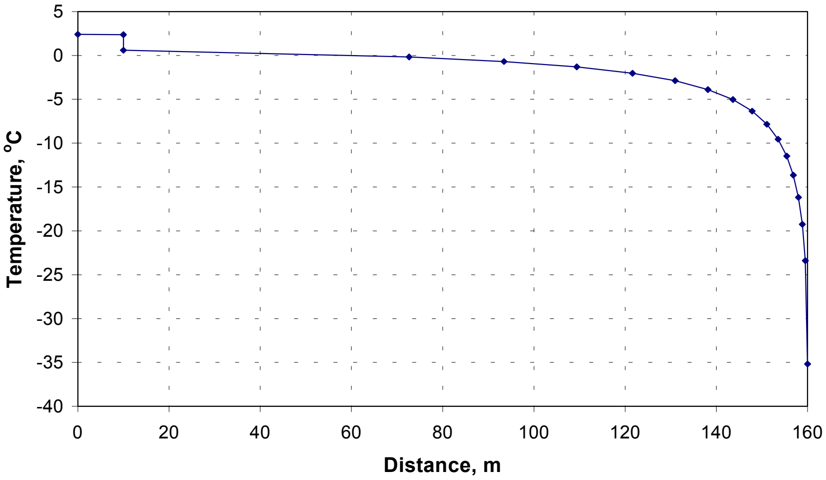

Fig. 3. Changes in flow temperature with distance

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 meters (33 ft) before the outflow end. However, in the last 10 m (33 ft) 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 part of the blow-off pipe but is powerful in the last one tenth.

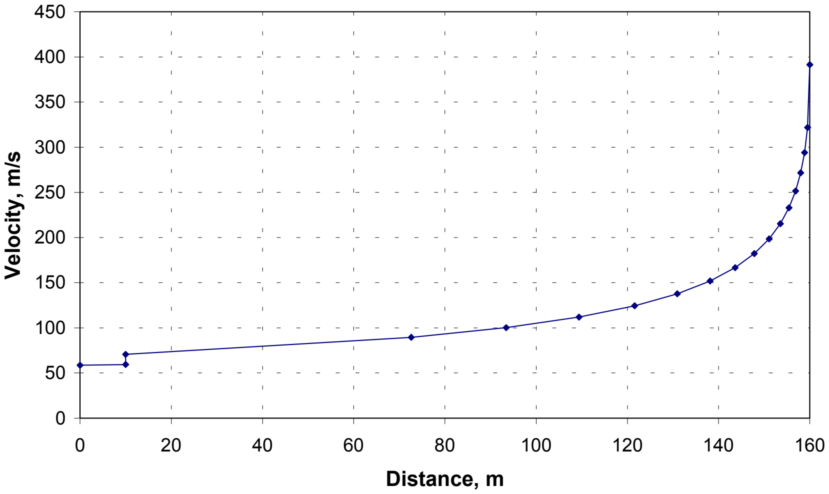

Fig. 4. Changes in flow velocity with distance

Temperature of the gas flow changes as a result of adjustment and expansion. Figure 4 shows that temperature at the beginning point of the blow-off system is 2.4 °C (36.3 °F), after adjustment it is 1.8 °C (35.2 °F) lower. There is significant cooling during the flare process at the outflow end where temperature reaches the lowest value -35 °C (-31 °F).

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 (4.3 psi) because of low flow velocity. At the output point of the control valve pressure is 17.2 bars (249 psi) because pressure decreases 3 bars (43 psi) during the control process. The pressure loss of 15.3 bars (222 psi) in the blow-off pipe is mainly due to the great gas flow. Eventually, pressure at the outflow end is 2 bars (24 psi) higher than ambient pressure.

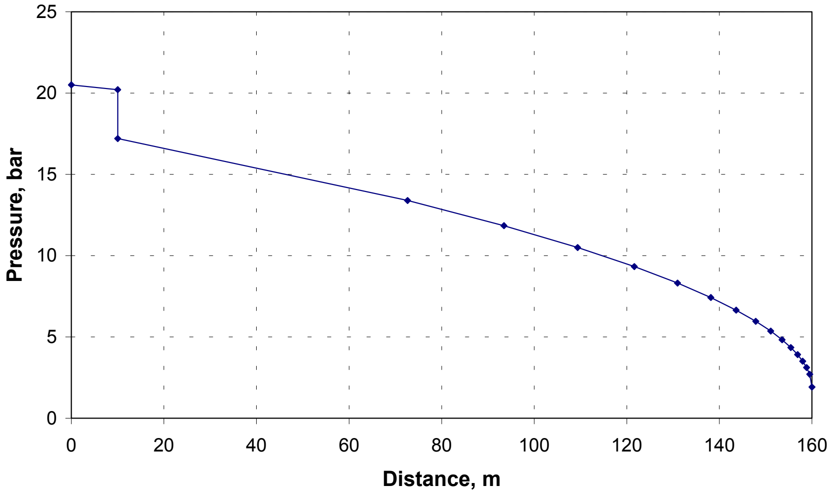

Fig. 5. Changes in pressure with distance

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 ND (4 in.) pipeline. While the Mach-number is below 1, pressure is equal to environmental pressure, i.e. there is no overpressure. In this domain the output volume 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. In this domain pressure at the outflow end will exceed ambient pressure.

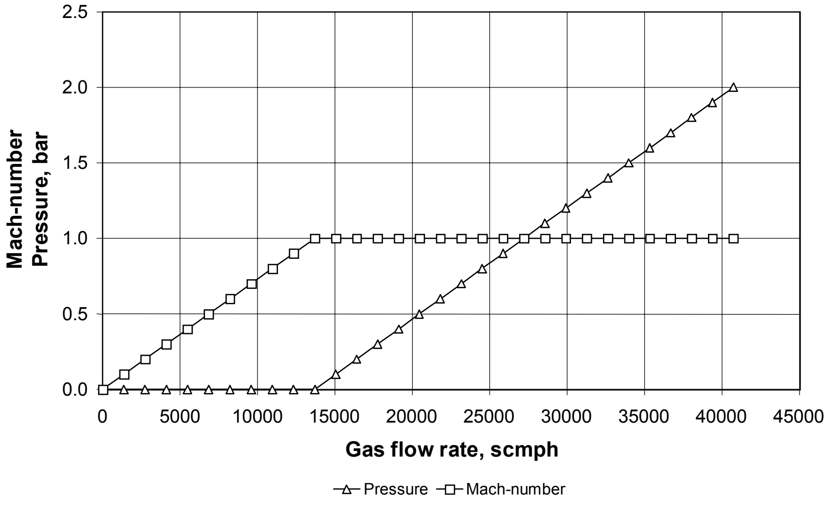

Fig. 6. Gas flow rate vs. the Mach-number and pressure

EXAMPLE

The examined system is a 15 km (9.3 mile) long 600 ND (24 in.) pipeline section, in which pressure at the beginning of the blow-off process is 25 bars (363 psi), and (soil) temperature is 5 ^{o}C (41 ^{o}F). The flare system consists of a 10 m long linking pipe, an adjusting valve and a 150 m (492 ft) long blow-off pipe with 100 ND (4 in.).

When processing calculation 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 flowing 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 (43.5 psi),

the volume of the controlled gas flow is a constant of 15 Mscmph (530 Mscfph),

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 great, then fast decreasing gas flow. At constant gas flow first great, 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.

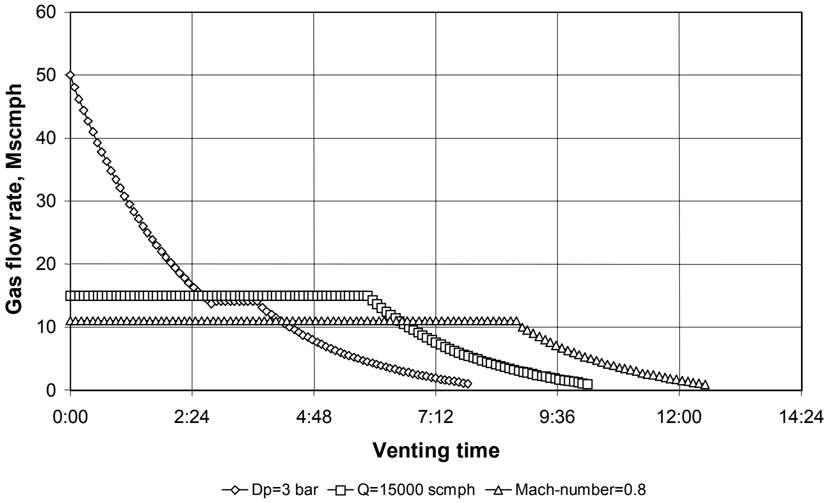

Fig. 7. Comparing control methods

CONTROL AT GIVEN PRESSURE DIFFERENCE

The constant pressure decrease at the adjusting valve is 3 bars (43.5 psi). 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 (43.5 psi) 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 decreases 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.

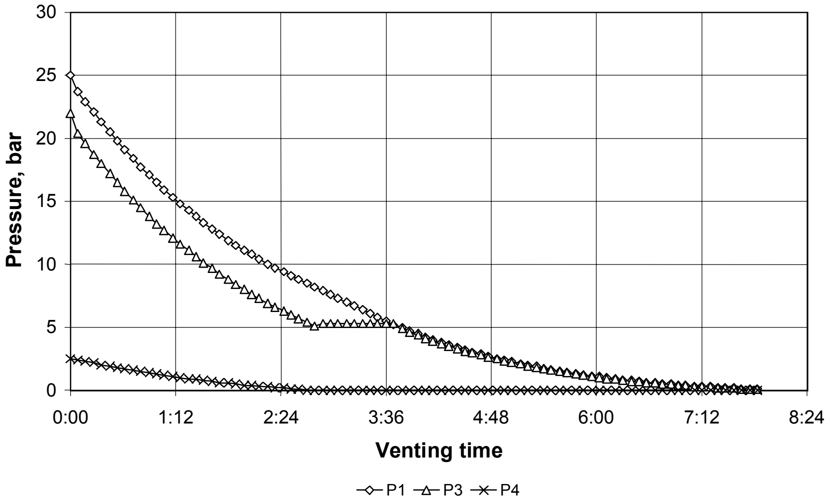

Fig. 8. Pressure change in time

In the first phase when pressures p_1 and p_3 decrease simultaneously, p_4 at the outflow cross-section is higher than surrounding 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 (72.5 psi). 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 surrounding pressure.

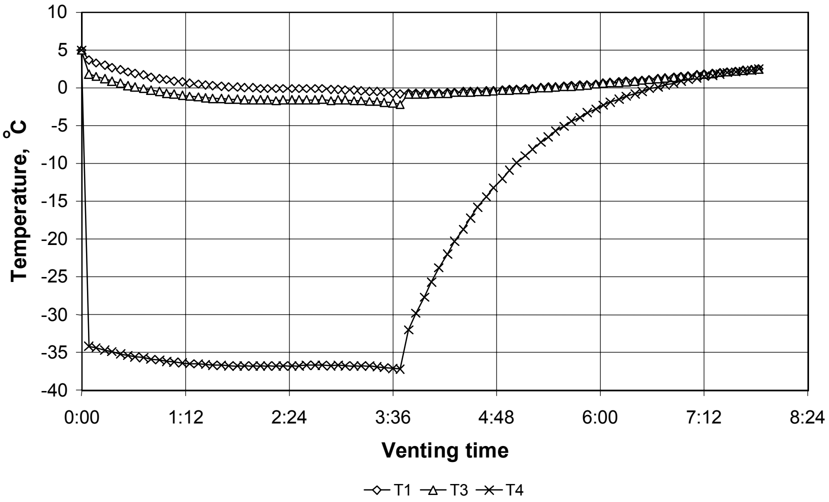

Fig. 9. Change of temperature in time

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 (41 ^{o}F) to –0.8 ^{o}C (30.6 ^{o}F), 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 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 shows that gas velocity reaches sonic speed in the phase of throttling controlling when $\Delta p > 0$, i.e. the 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.

The 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.

CONTROL AT GIVEN GAS FLOW RATE

Now the blow-off gas flow rate is a constant of 15 Mscmph (530 Mscfph). Figure 11 shows that the flare process using this control method lasts longer than using the previous method. Stagnation pressure decreases below 5 bars (72.5 psi) only after 6 hours. With the previous method the same extent of pressure decrease occurs after 3 hours 47 minutes.

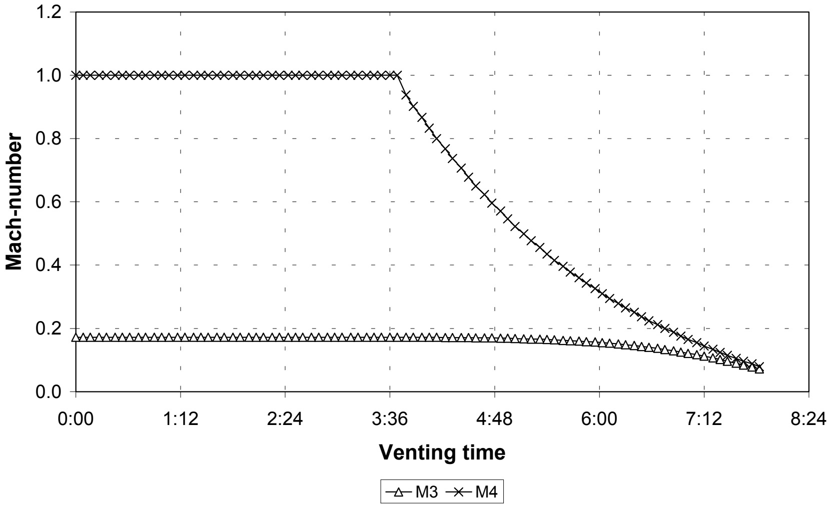

Fig. 10. Changes in the Mach-number vs. time

The first phase of blow-off lasts 5 hours 51 minutes. Until this point the gas flow rate of 15 Mscmph (530 Mscfph) can be ensured by reducing throttling. At the output point of the control valve, a pressure of 5.7 bars (82.7 psi) has to be sustained, and at the outflow end an overpressure of 0.1 bar develops. After 5 hours 51 minutes stagnation pressure and the pressure before the control valve decrease to an extent that throttling has to be ceased. From this point on the blow-off process is continued with completely open control valve and gradually decreasing gas flow. In the last phase the outflow pressure is equal to surrounding pressure, but the Mach-number continuously decreases. The blow-off process ends after 10 hours 11 minutes.

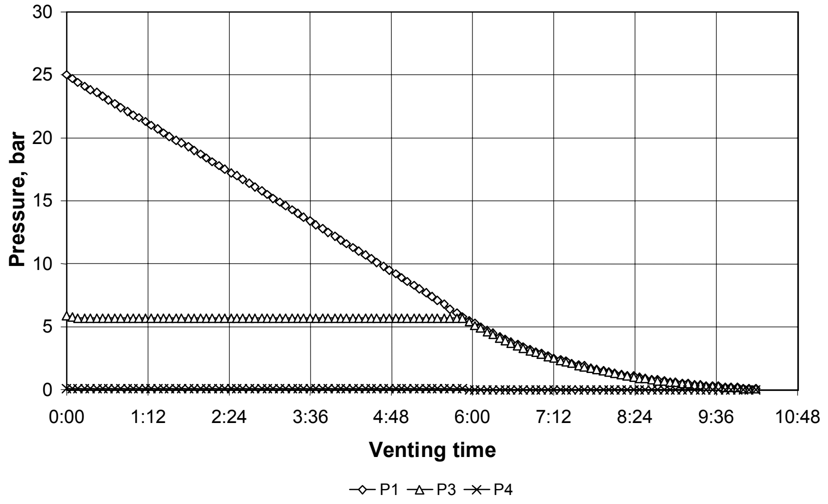

Fig. 11. Changes in pressure vs. time

Figure 12 shows that stagnation temperature T_1 decreases almost linearly from the initial soil temperature of 5 ^{o}C (41 ^{o}F) to –0.2 ^{o}C (31.6 ^{o}F). Peculiar to blow-off at constant gas flow, expansion in the "reservoir" and in the control valve equalise each other, thus temperature T_3 at the adjusting output point is nearly constant in the first phase. In the meantime a very low, but nearly constant temperature T_4 develops at the outflow end of the stack, since there is a significant expansion as flow velocity reaches sonic speed.

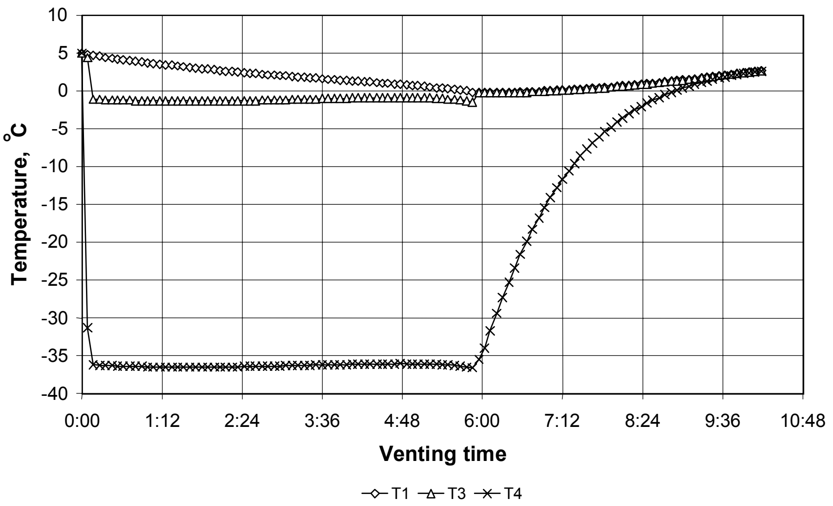

Fig. 12. Changes in temperature vs. time

In the second phase of the blow-off process, expansion rapidly decreases at all the points of the system, therefore temperature decreases at a lower pace. The figure shows that at temperatures T_1 and T_3 the change is smaller than at the outflow temperature T_4.

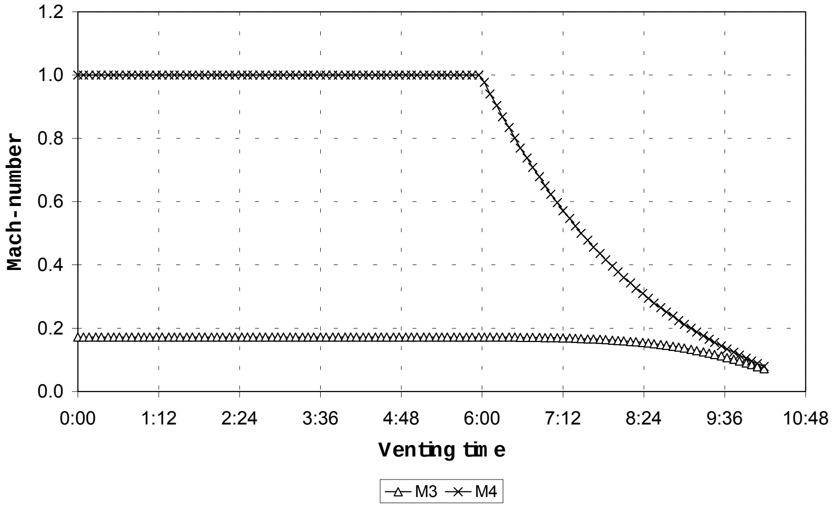

Fig. 13. Changes in the Mach-number vs. time

Examining changes in the Mach-number in Figure 13 we can see that at the outflow end Mach-number M_4 stands at 1 while the gas volume is a given constant. Afterwards, the Mach-number shows a low decrease after the control valve, but decreases significantly at the outflow end.

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 flowing under normal operation of gas transportation systems. It is reasonable to divide the system into two parts: the closed section of 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 non-steady 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. On the basis of the results one can see that the new software is suitable for either planning a new blow-off system or analyzing the blow-off process in an existing system.

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NOMENCLATURE

a	acoustic velocity, m/s
$\mathbf{c_s}$	specific heat of pipeline steel, J/kg.K
$\mathbf{c_g}$	specific heat of gas, J/kg.K
D	pipeline diameter, m
F	internal surface of the closed section of main pipeline, m^2
$\mathbf{f_D}$	Darcy friction factor
k	overall heat transfer coefficient, W/m^2.K.
dl	length of infinitesimal section, m
L	length of pipeline, m
M	local Mach-number, M=v/a
$\mathbf{M_g}$	molecular weight, kg/kmol
$\mathbf{m_s}$	weight of the main pipeline section, kg
$\mathbf{m_g}$	weight of the gas in the closed pipeline section, kg
κ	isentropic exponent of gas,
p	local pressure, Pa
$\mathbf{p_0}$	stagnation pressure, Pa
$\mathbf{p_s}$	static pressure (it depends on Mach-number), Pa
R	gas constant (8314), J/kmol.K
T	local temperature, K
$\mathbf{T_0}$	stagnation temperature, K
$\mathbf{T_s}$	static temperature (it depends on Mach-number), K
$\mathbf{T_t}$	soil temperature, K
v	actual velocity of gas, m/s
$\mathbf{V_{pipe}}$	volume of the closed pipeline section, m^3
z	compressibility factor at p and T, -
ρ	gas density at p and T, kg/m^3