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Andrzej Rusin*
Katarzyna Stolecka

Silesian University of Technology
Institute of Power Engineering and Turbomachinery
Gliwice

An analysis of the phenomena accompanying an uncontrolled leakage of CO_2 from a damaged pipeline

The further use of coal as fuel in new power plants depends on the application of technologies reducing CO_2 emissions into the atmosphere. For this reason, research is being carried out on the gas capture and storage methods. In future, these new technologies will require a new pipeline infrastructure for the transportation of carbon dioxide to storage locations. An important aspect of the transport of CO_2 is the assessment of the effects of an uncontrolled release of gas from a damaged pipeline. A reliable assessment of these effects calls for the modelling of the phenomena related to the CO_2 leakage. The thermodynamic and flow aspects of the phenomena occurring in a damaged pipeline and in its environment are discussed in this paper. The mathematical models of these phenomena are described and examples of calculations of the changes in CO_2 parameters after the damage to the pipeline are presented.

Nomenclature

a – pipeline damege coefficient
G – mass flux density, kg/m^2/s
v – fluid specific volume, m^3/kg
h – fluid specific enthalpy, m^2/s^2
D – pipe diameter, m
q – heat flux density, kg/s^3
f – Fanning friction coefficient
A – surface area, m^2
u – velocity, m/s
p – pressure, Pa
η – liquid phase mass content
ρ – density, kg/m^3

*Corresponding author. E-mail address: andrzej.rusin@polsl.pl

1 Introduction

Poland is a country where electricity generation based on the combustion of hard and brown coal. The further use of these fuels depends on the application of technologies reducing CO_2 emissions into the atmosphere because an excessive concentration of this gas is believed to be the cause of climate changes. For this reason, research is being carried out on the gas capture and storage (CCS) methods. In future, these new technologies will require a new pipeline infrastructure for the transportation of CO_2 to storage locations. An important aspect of the transport of gas is the assessment of the effects of an uncontrolled release of gas from a damaged pipeline. A leakage of this kind may result from damage to the pipeline caused by wall corrosion or by human errors during earth works near the pipeline [1]. A reliable assessment of these effects calls for the modelling of the phenomena related to the CO_2 leakage. The thermodynamic and flow aspects of the phenomena occurring in a damaged pipeline and in its environment are discussed in this paper. Special attention is given to the modelling of the two-phase flow in the pipeline which appears upon a sudden drop in pressure and upon evaporation of the liquid phase. Additional expansion and a further change in parameters occurs after CO_2 is released into the environment. The calculations of the changes in pressure and temperature, as well as those related to the velocity and the gas mass flux in the pipeline and in the hole, are performed using the PHAST v6.7 software.

2 Carbon dioxide properties

Carbon dioxide – CO_2 is a colourless and odourless gas. It is nonflammable and nonexplosive. It is a natural organic compound which is well soluble in water. Together with oxygen and nitrogen it is the air natural component. Its concentration in atmosphere is approximately 385 ppm. Carbon dioxide features a higher density than air. It is a greenhouse gas, but on the other hand – it is used by plants in photosynthesis. It may occur naturally or as a result of the combustion of solid, liquid or gaseous fuels. It may also be obtained from many processes, such as oxidation and fermentation in distilleries or wine factories. Carbon dioxide may also be released during the extraction of raw materials in mining shafts and as a consequence of the rock mass movement. It may also be one of the effects of a volcanic eruption. Depending on pressure and temperature, carbon dioxide may occur in various states of aggregation, i.e., as a solid (dry ice), a liquid, a vapour, a gas (supercritical region). The carbon dioxide critical point is the pressure of 72.8 bar and the temperature of 304.1 K. Above the critical point in the supercritical region carbon dioxide features the density of a liquid, and the viscosity and compressibility of a gas. The diagram of carbon dioxide phase transitions is presented in Fig. 1. Carbon dioxide finds numerous applications, e.g., in the sugar industry, the food industry (as a fizzy drink ingredient), the chemical industry (production of chemicals) and in fire-fighting [2]. Due to its physicochemical properties, carbon dioxide is also highly valued as a cooling agent. Compared to other agents, it features, among others, a low flow resistance and it is inert to food products [3].

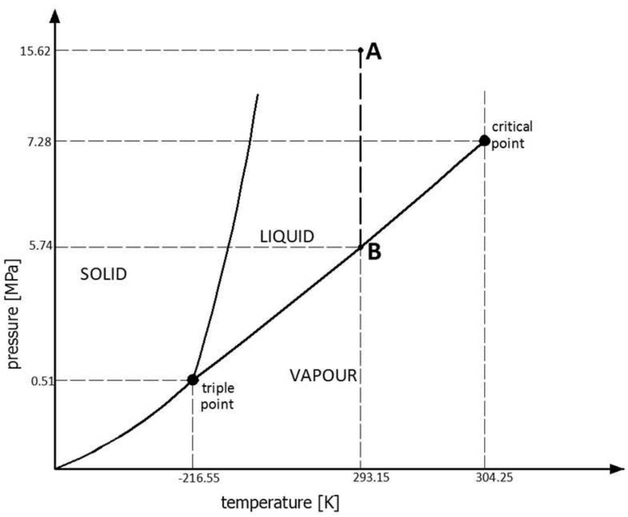

Figure 1. Phase diagram of carbon dioxide.

Although carbon dioxide is a nonflammable and nonexplosive gas, it poses a death hazard due to suffocation. As carbon dioxide features a higher density than air, it displaces air from the room. According to the World Health Organisation, the permissible level of CO_2 concentration in rooms is 1000 ppm. Carbon dioxide concentration in atmosphere is approximately 385 ppm (0.04% by volume) and this value should not be exceeded as higher concentrations are harmful to humans. A concentration at the level of 350–450 ppm creates ideal conditions. Certain higher concentrations of CO_2 in air are considered permissible. One of them is 1.5%, which is the tolerance dose for employees under continuous medical care who work in special conditions, e.g., on spaceships. The fact that carbon dioxide is odourless makes it impossible to detect that its concentration has been exceeded. Therefore, the use of leak detectors is recommended to find out about leakages in the installation. The concentration of carbon dioxide between 2 and 5% causes deeper and faster breath; headaches and ear buzzing may appear as well. At higher concentrations of 8–10% the pulse races and the blood pressure rises; a feeling of disorientation appears. Concentrations of 10–20% bring on hallucinations, convulsions and loss of consciousness. Spending more time in concentrations higher than 20% may cause death. Concentrations exceeding 30% cause immediate death [4,5].

Due to the hazards presented above, the CCS technologies should be assessed in relation to the risk created at all stages of the process, i.e., at the capture, transport and storage of CO_2. A leakage of CO_2 from transport pipelines, presenting hazard to humans and animals in the area of the cloud of the released gas, may occur at the transport stage. Another risk is exposure to the jet of gas with a very low temperature. The assessment of these hazards requires first and foremost the identification and development of the model of the phenomena that take place in a damaged pipeline.

3 The model of phenomena occurring in a damaged pipeline

Immediately after the pipeline is damaged, the pressure of the condensed CO_2 decreases abruptly. The rate of this drop depends on the speed of sound in this liquid. In the final phase of the process in the pipeline CO_2 reaches the parameters of a saturated liquid. The course of the process may in fact be complicated significantly by factors such as waves generated in the pipeline or the impact of the elasticity of the pipeline itself. Thermodynamically, this process is not a simple process of isentropic, isenthalpic or isothermal expansion, but experimental measurements show that no substantial changes in temperature occur in it. Considering subsequent phenomena, it is justified to assume that at, the end of this process the parameters that correspond to the initial temperature T_0, and to the saturation pressure in this temperature, $p_0 = p_{sat}(T_0)$, stabilise in the pipeline. Now the process of evaporation starts and a further drop in pressure at the expense of the heat absorbed from the liquid and the pipeline walls occurs. Evaporation begins at the location of the rupture and moves towards the pipeline end. This means that in either of the two parts of the pipeline determined by the rupture there exist two zones: the saturated liquid zone (1) with constant temperature T_0 and pressure p_0 and a two-phase zone (2). The content of the gas fraction in the zone (2) changes from zero in the 'b' cross- section separating the zones (1) and (2) to one in the outflow area (Fig. 2). The liquid flows towards the hole with an increasing content of the gas fraction and a simultaneous decrease in pressure to a certain value of p_e at the place of the outflow. The flow velocity in the zone (2) is therefore a resultant of the drop in pressure and the rate of expansion caused by evaporation. With the mass of CO_2 decreasing in the pipeline, the boundary 'b' separating the zones moves towards the pipeline end, eventually reaching it if in the pipeline there is no flow forced by a pump. This means that the zone (1) disappears. If at the end of the pipeline there is a pump still working to ensure a certain constant flow, the boundary 'b' separating the zones may hold at a certain location resulting from the equilibrium between the inflow of the liquid forced by the pump and the outflow at the place of damage to the pipeline. If the boundary 'b' separating the zones reaches the pipeline end, a two-phase flow occurs in the entire pipeline. There is still the pressure gradient related to the evaporation of the liquid phase, which causes the gas to be released through the hole. From this moment, the pressure at the beginning of the pipeline starts to drop and the process lasts until the pressure in the entire pipeline and in the hole becomes equal to ambient pressure. Then practically the whole content of carbon dioxide in the pipeline is released into the environment [6].

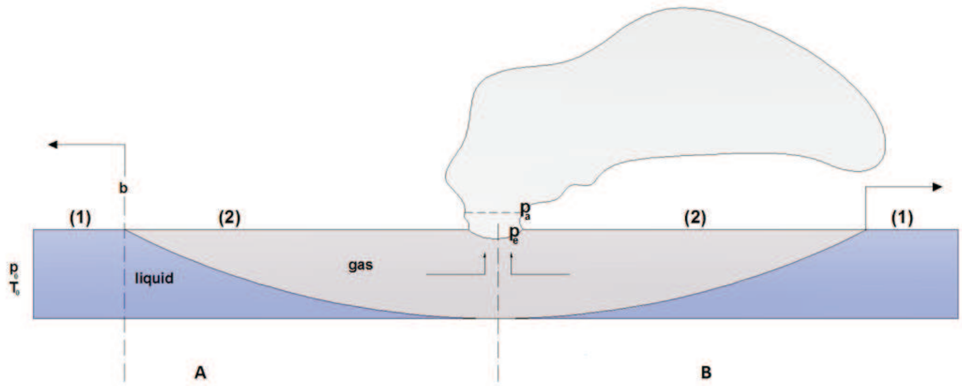

Figure 2. The release of gas from a damaged gas pipeline.

The equations of state that describe the behaviour of carbon dioxide in two-phase flows, assuming a homogeneous equilibrium model, have a common form for both temperature and pressure:

$$T = T_{sat}(p) \qquad \text{or} \qquad p = p_{sat}(T) \ . \tag{1}$$

The specific volume, v, and the specific enthalpy, h, are described by the following relationships:

$$v = \eta v_l + (1-\eta)\, v_g \ , \tag{2}$$

$$h = \eta h_l + (1-\eta)\, h_g \ , \tag{3}$$

where η is the liquid phase mass content and the subscripts l and g denote the liquid and gaseous phase, respectively. The equations of conservation of mass, momentum and energy describe the one-dimensional model of flow implemented in the PHAST v6.7 system [6] in forms related to the unit of the pipe cross-section surface area:

$$\frac{\partial}{\partial t}\left(\frac{1}{v}\right) + \frac{\partial G}{\partial x} = 0 \ , \tag{4}$$

$$\frac{\partial G}{\partial t} + \frac{\partial (G^2 + p)}{\partial x} = -2f \frac{G\,|G|\,v}{D} \ , \tag{5}$$

$$\frac{\partial \left[\frac{h+pv+\frac{G^2v^2}{2}}{v}\right]}{\partial t} + \frac{\partial \left[\left(h + \frac{G^2v^2}{2}\right) G\right]}{\partial x} = \frac{4q}{D} \ , \tag{6}$$

where in Eqs. (4)–(6):

- G – mass flux density [kg/m^2/s],
- v – fluid specific volume [m^3/kg],
- h – fluid specific enthalpy [m^2/s^2],
- D – pipe diameter [m],
- p – pressure [Pa],
- q – heat flux density [kg/s^3],
- f – Fanning friction coefficient.

Knowing the heat flux q, the equations given above together with the equations of state for carbon dioxide allow the calculation of the gas parameters in the pipeline. An essential feature of the CO_2 flow in the zone (2) is the boundary separating the gaseous and the liquid phases that moves towards the pipeline ends. The speed of this movement is much slower than the velocity of CO_2 leaking into the environment through the hole. For this reason, it is justified to assume a quasi-steady flow in the two-phase zone. This assumption makes it possible to simplify the dependences (4)–(6). When the boundary separating the zones reaches the pipeline end, the pressure and the temperature fall and, together with the flow, they become dependent on time again, according to the Eqs. (4)–(6). The outflow of gas through the hole in the pipeline is most of the time a throttled one. This results in the occurrence of atmospheric expansion to ambient pressure in the immediate vicinity of the hole. This phenomenon causes a further reduction in the liquid phase, a rise in the velocity, and the CO_2 temperature reaches the saturation point at atmospheric pressure. The physical phenomena occurring during the outflow through the hole are described in the model implemented in the PHAST v6.7 system [6] by the following equations:

$$\rho_f A_f u_f = \rho_o A_o u_o \ , \tag{7}$$

$$\rho_f A_f u_f^2 = \rho_o A_o u_o^2 + (p_o - p_f) A_o \ , \tag{8}$$

$$\rho_f A_f u_f \big[h_f + \frac{1}{2} u_f^2\big] = \rho_o A_o u_o [h_o(p_o, T_o) + \frac{1}{2} u_o^2] \ , \tag{9}$$

$$\rho_f = \rho_f(p_a, T_f) \ , \tag{10}$$

$$h_f = h(p_a, T_f) = \eta h_l(p_a, T_f) + (1-\eta) h_g(p_a, T_f) \ , \tag{11}$$

where A – surface area and ρ is the density. The subscript o denotes the parameters in the orifice, subscript a ambient parameters and f is the parameters after expansion in the atmosphere. By solving the system of equations presented above, it is possible to calculate the parameters of the agent after its expansion in the atmosphere.

4 An analysis of the phenomena in the pipeline

The first stage of the studies on the effects of the CO_2 leakage from a damaged pipeline is the analysis of the phenomena occurring in the pipeline itself. The calculations are performed using the PHAST v6.7 software with implemented models described in Section 3. Detailed calculations are made for 0.5 km long pipeline with three different diameters: 0.2, 0.3 and 0.45 m. In each case the analysis relates to the pipeline damage characterised by the coefficient a, which is the ratio of the equivalent diameter of the gas outflow hole to the diameter of the pipeline. In the calculations it is assumed that $a = 0.2$. It is also assumed that the CO_2 parameters in the pipeline before damage are as follows: temperature 20 °C, pressure 15.26 MPa. Due to the damage, an abrupt pressure drop occurs in the pipeline to saturation pressure in the temperature of 20 °C, i.e., to 5.74 MPa. It is assumed that in each case the damage occurs in the middle of the pipeline, dividing it into two parts (Fig. 2).

The results of the changes in parameters in the damaged pipeline are given for the areas inside the pipeline and in the hole through which the gas is released into the environment. The subsequent figures relate to a single part of the pipeline with the length of 0.5 km, from the gas inflow side. Figures 3 and 4 present the changes in parameters, i.e., the changes in the CO_2 pressure and temperature in the inlet part of the pipeline, depending on time. Figure 5 shows the change in the content of the liquid phase depending on time.

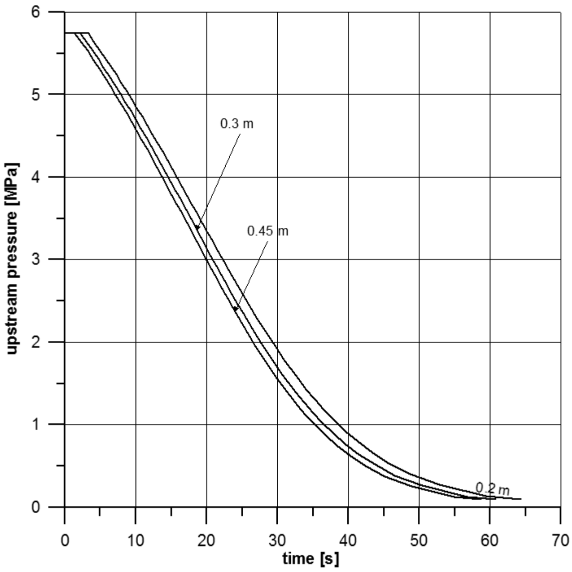

Figure 3. The change in the CO_2 pressure in the damaged pipeline depending on time.

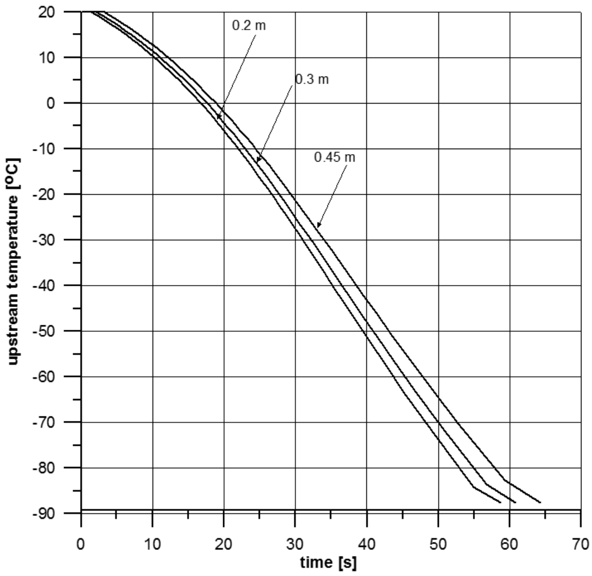

Figure 4. The change in the CO_2 temperature in the damaged pipeline depending on time.

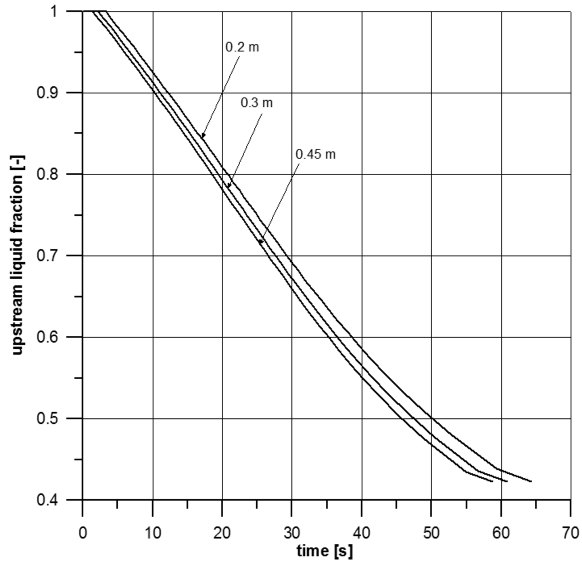

Figure 5. The change in the content of the CO_2 liquid phase in the damaged pipeline depending on time.

The presented data indicate that the boundary separating the liquid phase from the gaseous phase reaches the pipeline beginning within 3–4 s. The next figures present the changes in the parameters of the medium in the hole resulting from damage. Figure 6 shows the changes in the mass flux in the hole, Fig. 7 – the changes in temperature and Fig. 8 – the changes in the pressure in the hole, depending on time. The changes in the outflow velocity depending on time are presented in Fig. 9. Figure 10 shows the changes in the amount of the gas released from a single part of the gas pipeline. The change in the length of the zone (2) with a two-phase flow is presented in Fig. 11. After the gas is released into the environment, it is expanded further. The change in the gas outflow velocity after expansion is shown in Fig. 12.

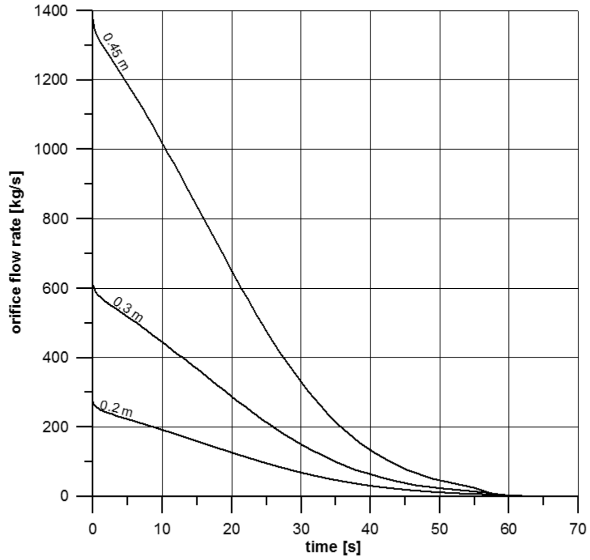

Figure 6. The change in the CO_2 mass flux in the orifice depending on time.

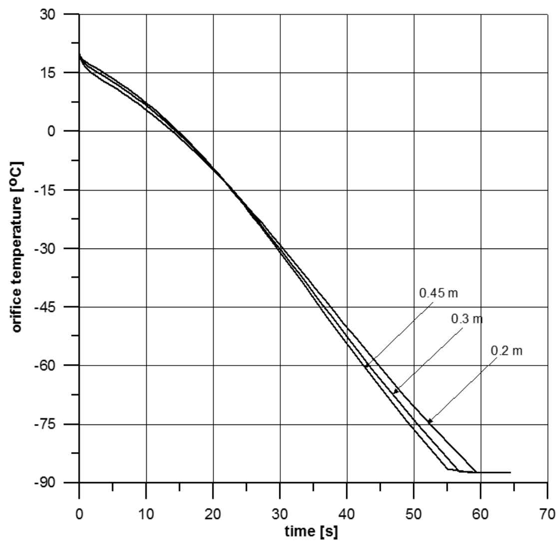

Figure 7. The change in the CO_2 temperature in the orifice depending on time.

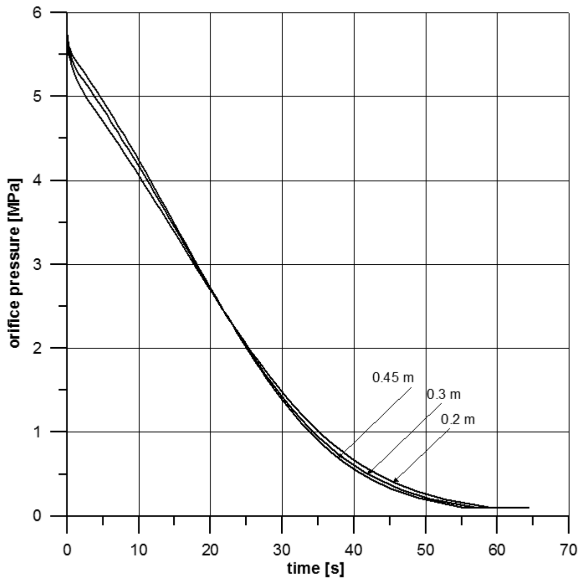

Figure 8. The change in the CO_2 pressure in the orifice depending on time.

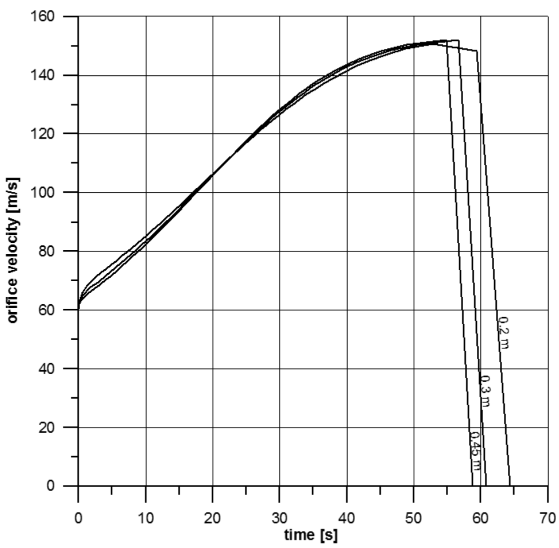

Figure 9. The change in the CO_2 outflow velocity in the orifice depending on time.

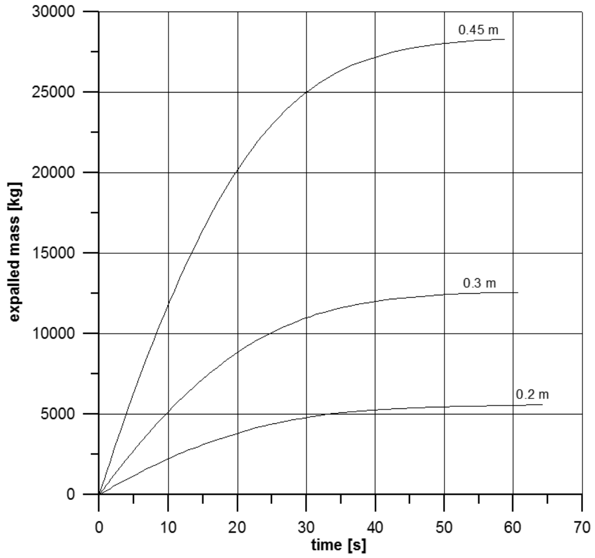

Figure 10. The change in the amount of gas released from part A of the gas pipeline depending on time.

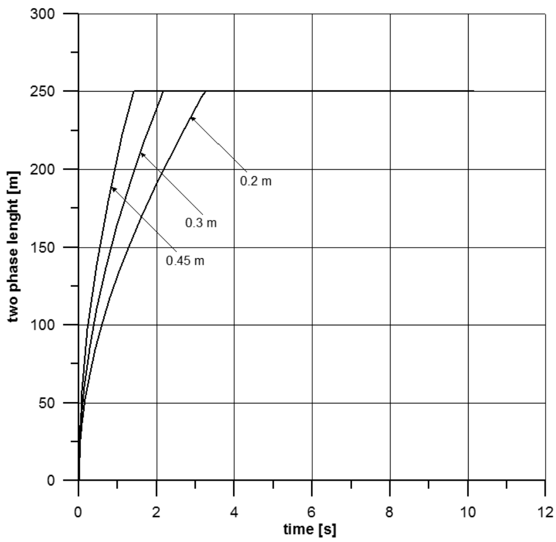

Figure 11. The change in the length of the zone (2) with a two-phase flow depending on time.

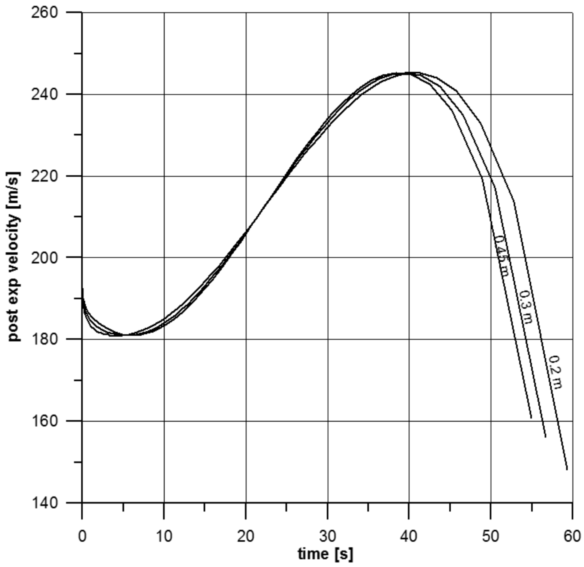

Figure 12. The velocity of the gas outflow after expansion in the environment depending on time.

5 Conclusions

The performed analysis of the phenomena that occur after damage to the pipeline transporting CO_2 gives an idea of the violent changes in the state of the gas both in the pipeline and after it is released into the environment. An essential component of these changes is the evaporation of the CO_2 liquid phase and the appearance of a two-phase flow. These changes alter both the gas flow and outflow velocity on the one hand and reduce its temperature on the other. This also causes a decrease in the pipeline wall temperature. After the gas is released into the environment, a cloud is formed. The size of this cloud depends on the amount of the released gas and the cloud moves in the direction that depends on wind direction. A high CO_2 concentration in the cloud moving near the ground may present serious hazard to human health and life.

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Analiza zjawisk przy niekontrolowanym wycieku CO_2 z uszkodzonego gazociągu

S t r e s z c z e n i e

Dalsze wykorzystanie węgla jako paliwa w nowych blokach energetycznych uzależnione jest od stosowania technologii obniżających emisje CO_2 do atmosfery. W związku z tym wciąż trwają badania nad metodami wychwytu i magazynowania tego gazu. Te nowe technologie wymagać będą w przyszłości powstania infrastruktury rurociągowej w celu przesyłu dwutlenku węgla do miejsc składowania. Ważnym aspektem transportu CO_2 jest ocena skutków niekontrolowanego wycieku tego gazu z uszkodzonego rurociągu. Wiarygodna ocena tych skutków wymaga modelowania zjawisk związanych z wypływem CO2. W artykule omówiono aspekty termodynamiczne i przepływowe zjawisk zachodzących w uszkodzonym rurociągu i jego otoczeniu. Opisano modele matematyczne tych zjawisk, podano przykłady obliczeniowe zmiany parametrów dwutlenku węgla po uszkodzeniu rurociągu.