

Hazards of hydrogen transport in the existing natural gas pipeline network

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Abstract

The development of European economies will occur in parallel with efforts aiming to reduce the use of fossil fuels in power generation and transport. This has led to an increased interest in hydrogen as the energy carrier of the future. However, before hydrogen can be used efficiently on a large scale, a new hydrogen-based economy will have to be developed to serve gas production, storage and transport needs. An alternative to what would be rather costly investment in new infrastructure could be to use the existing network of gas pipelines by adding hydrogen to natural gas and transporting the mixture. The new solution should be considered in terms of research on the technological adaptation of the existing pipelines (appropriate fixtures and fittings, materials, pipeline geometry) as well as on possible consequences of a potential failure and the related serious hazards. The paper presents the results of an analysis of the effects of a jet fire arising due to an uncontrolled release of natural gas and its mixture with hydrogen from a pipeline. The impact of the variability in the gas and the pipeline parameters on the severity of the consequences is shown.

Keywords: natural gas/hydrogen mixture, pipeline, hazard, jet fire

1. Introduction

A sustainable energy policy should rely on numerous variants of obtaining energy carriers and their distribution. This primarily concerns fossil fuels, which should be utilized in parallel with renewable energy sources. The most common gas energy carriers are mixtures of hydrocarbons composed mainly of methane. However, in recent year research has also focused on hydrogen because the gas is seen as a clean and economical energy carrier of the future. Its application should make it possible to reduce emissions of greenhouse gases (e.g., carbon dioxide) into the atmosphere. For this reason, hydrogen is viewed by many countries as an alternative to fossil fuels. Their governments believe that research on the gas utilization is worth pursuing. However, an essential problem in using hydrogen is the need to build appropriate infrastructure to ensure, among other things, safe and economical production, transport and utilization. The rise of a hydrogen-based economy may be a long and laborious process requiring heavy investment and substantial technological change [1–3].

It is generally considered that the most economical hydrogen transmission system is pipeline transport. However, the problem is that in the design of pipelines intended for

the transport of hydrogen account must be taken of the enhanced embrittlement and corrosion of steel this necessarily involves. One of the methods that may enable the use of hydrogen and mitigate this negative effect is to send the gas through existing networks of pipelines in the form of a mixture with natural gas, for example. Another solution is to design a network intended specially for the transport of a hydrogen/natural gas mixture at appropriate values of pressure, using special materials and selecting specific dimensions. This method, however, will require a number of tests, considerable investment outlays and lengthy construction works [4]. The fact that methane and hydrogen differ in physiochemical properties also causes problems when piggy-backing networks of gas pipelines designed, built and used based on the assumption that the transported medium will be natural gas only. The problems relate to the unfavorable impact of the mixture on the pipeline network integrity and working life and to the higher level of hazard posed to humans and the environment in the event of failure [4, 5].

No matter which scenario of actions is selected, the problem of adding hydrogen to natural gas calls for an analysis of many technical and safety-related issues. The hydrogen embrittlement caused by the presence of hydrogen in the pipeline may increase the probability of pipeline failure and an uncontrollable release of the hydrogen/natural gas mixture. The paper presents analyses related to an uncontrollable release of methane and a methane/hydrogen mixture

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from a pipeline. The issue also includes an analysis of the consequences of failure in the form of a jet fire [6–8].

2. Hydrogen in the gas network

In normal conditions, adding relatively low concentrations of hydrogen to the existing gas network may require only minor modifications in the structure and operation of individual elements and pipelines. Generally, the permissible amount of hydrogen in the mixture in the gas network should be determined individually, depending on the network structure, the natural gas parameters and composition and the end users' requirements. The results of the testing performed to date indicate that a hydrogen volume content of 5 .. 15% should have no essential impact on the pipeline network reliability. If the content is in the range of 15 .. 50%, the effect becomes more significant. Contents higher than 50% create substantial challenges in a number of aspects, including selection of appropriate materials for pipeline construction to ensure resistance to hydrogen penetration into intercrystalline structures of steel, safety issues and necessary modifications to the end users' equipment. For example, the maximum permissible concentration of hydrogen in the network in Holland and Germany is 2 and 5%, respectively [7].

The German Scientific and Technical Association for Gas and Water (DVGW) carried out detailed testing to determine the maximum safe concentration of hydrogen in the mixture with natural gas for various elements of the entire gas system. Five stages of the gas delivery chain were defined: transport, storage, metering/regulation, distribution and use. Three thresholds of hydrogen concentration in the mixture were also specified. The first means that adding hydrogen to natural gas does not harm the installation element; the second, that the introduction of the hydrogen/natural gas mixture requires appropriate technological or administrative adaptations; the third requires that tests concerning the adding of hydrogen and the impact thereof on the infrastructure elements should be continued. Fig. 1 and Fig. 2, respectively, present results of analyses conducted with regard to the elements of the gas transmission network (transport stage) and of the distribution system. The contents of hydrogen relate to the three thresholds of hydrogen concentration in the mixture with natural gas [9].

Hydrogen has an unfavorable impact on metal properties, which may substantially modify the process of gas transport as a mixture with natural gas. It weakens the mechanical strength of metals and increases embrittlement. Moreover, the presence of hydrogen in metals intensifies corrosion. As hydrogen penetrates into the structure of steel, it changes its mechanical and usable properties. The degree of the changes depends on the steel's chemical composition and microstructure, and type of thermal treatment, etc. Hydrogen is able to diffuse into crystalline structures of metals owing to the small size of the gas particles. The testing results obtained to date indicate that the intensity of the phenomenon depends, among others, on temperature, pressure, the state of the structure surface, the stress state and the content of

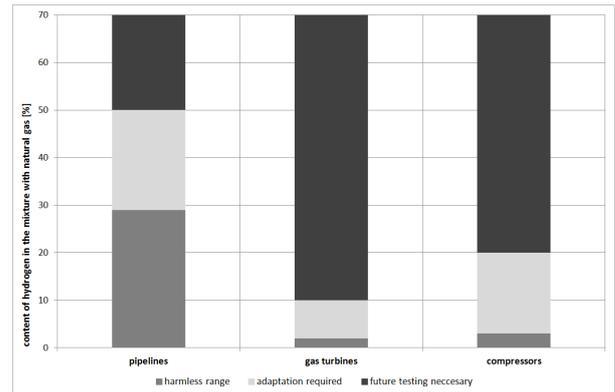


Figure 1: Impact of the content of hydrogen in the mixture with natural gas on the transmission system elements [9]

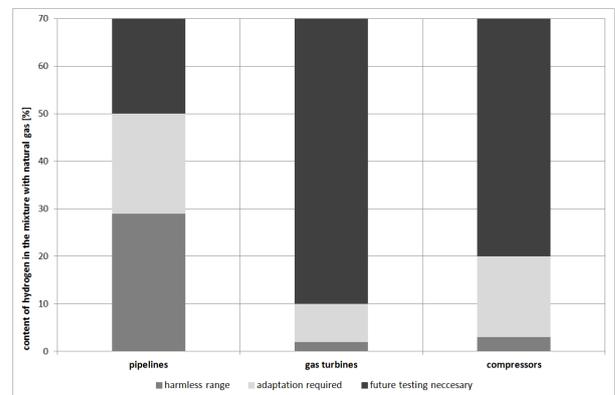


Figure 2: Impact of the content of hydrogen in the mixture with natural gas on selected elements of the distribution system [9]

individual chemical elements in the steel composition. Hydrogen affects areas of structural defects, non-metallic inclusions, and grain dislocations. This impact, depending on its mechanism, affects the processes of hydrogen destruction of metals and substantially impacts pipeline reliability and the gas transport process. Permissible contents of hydrogen in a mixture with natural gas at levels lower than 5%—specified for compressors and turbines—result from the high sensitivity of low-emission burners used in gas turbines to the presence of hydrogen. In the case of compressors, the permissible limit is set in light of the need to increase gas throughput (mass/volume flow). The same restriction concerns flow limiters used in distribution networks. The flow velocity of the methane/hydrogen mixture will be 1.7 times higher than pure methane (assuming the same flux of supplied energy) [9–11].

The impact of adding hydrogen to natural gas is also important if a failure occurs in the form of an uncontrollable release and ignition of the gas mixture.

3. Causes of pipeline damage

It should be remembered that adding hydrogen into an existing network intended for natural gas transmission requires

analyses in the field of technical and also safety-related issues. A characteristic feature of hydrogen, which substantially affects the safety of its use, is its wide range of flammability in air—from 4 to 75% V/V, whereas for methane, for example, the range is only 5.3 .. 15% V/V. Another property which has an impact on the potential danger of hydrogen catching fire is its low ignition point, i.e., the minimum amount of external energy which, if supplied to hydrogen, can cause it to ignite. The value for a stoichiometric mixture of hydrogen is only 0.02 mJ, whereas for other fuels the energies are more than ten times higher. Such a low value of minimum ignition energy for hydrogen leads to a situation where any uncontrollable leakage might end in a fire—the igniting spark can be caused merely by friction from the hydrogen jet itself or by the electrostatic influence of objects such as clothes. Another important value characterizing the hydrogen burning process is the burning rate, i.e., the rate at which the flame spreads through the combustible mixture of hydrogen. It is much higher than for other fuels and ranges from 2.65 to 3.25 m/s. The flame of burning hydrogen is almost invisible, and the phenomenon of soot formation does not occur in it. Adding hydrogen to an existing gas network can thus significantly increase the hazard resulting from failure and an uncontrollable release of the substance. Uncontrolled release and ignition may cause a jet fire, which is extremely dangerous for both humans and property. Explosion is also a possible consequence [7, 12, 13].

Although research on operating safety and minimizing the risk of gas pipeline failure has been ongoing for many years, it is impossible to eliminate all causes of damage to the installation. Pipelines get damaged mainly due to factors such as corrosion, poor quality of weld seams, leaking valves and mechanical damage either natural or through human error. The causes of possible damage to pipelines are presented in Fig. 3, [14].

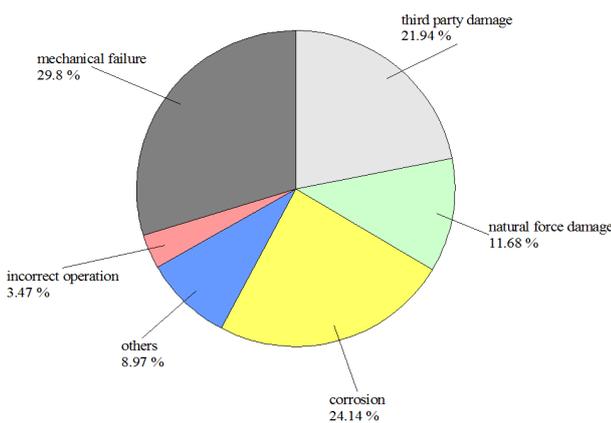


Figure 3: Causes of pipeline damage

The rate of occurrence of individual causes of pipeline damage estimated based on literature data is shown in Fig. 4. The data relate mainly to failures of natural gas pipelines. It should be noted that the probability of damage to pipelines transporting hydrogen mixtures is higher due to

enhanced embrittlement of the pipeline steel. Consequently, in the case of transport of a gas mixture, the total risk understood as the product of the probability of the gas pipeline failure and the effects thereof will be higher [2].

4. Negative effects of pipeline failure

Uncontrolled release and ignition of hydrogen mixtures may cause a fire and/or explosion. Physical effects of such events which pose extreme danger to humans and property are: the pressure wave from an explosion or, in the case of fire, heat flux and direct impact of the flame. The consequences of the failure will depend on the mixture parameters, the atmospheric conditions, pipeline geometry and the extent of pipeline damage (puncture damage or full-bore rupture (major damage to the pipeline)). The most common hazard arising due to pipeline failure is the jet fire mentioned above. The phenomenon is characterized by a long and stable flame, generating high thermal radiation. The fire is caused by the ignition of the gas jet released under high pressure through a hole in the pipeline. Estimation of the value of the heat flux generated by the jet fire flame is still a key subject of research, and the proposed models, such as source models, multi-point models and surface source models are approximate semi-empirical ones. The simplest method to determine the heat flux arising due to a jet fire is to use the following relation [7, 12]:

$$q = \frac{\eta \tau_a m H_c}{4\pi x^2} \tag{1}$$

where: η —content of radiated energy, m —released mass flow, H_c —combustion heat, x —distance between the receiver and the flame centre, τ_a —air transmissivity.

A more elaborate model that can be used to calculate the heat flux from a jet fire is the semi-empirical model based on Chamberlain's assumptions [15]. It makes it possible to forecast the shape and radiation of the flame. The model was developed based on long-standing research and experiments performed in a wind tunnel. In the presented model the flame shape is simulated using a truncated cone—a solid body radiating from the entire surface (cf. Fig. 5) [15–17].

The values of the heat flux generated by a fire which are dangerous for humans and property are listed in Table 1 [18].

Table 1: Thermal radiation effects on humans and property

heat flux	effects on humans
1.6 kW/m ²	no damage despite long exposure
4-5 kW/m ²	pain after 20 s; first-degree burns, cracking of glass after 30 s
9.5 kW/m ²	second-degree burns after 20 s
12.5-15 kW/m ²	first-degree burns after 10 s; 1% death rate within 1 min, melting of plastics (exposures exceeding 30 min)
25 kW/m ²	major injuries within 10 s; 100% death rate within 1 min, deformation of steel (exposures exceeding 30 min)
35-37.5 kW/m ²	1% death rate within 10 s

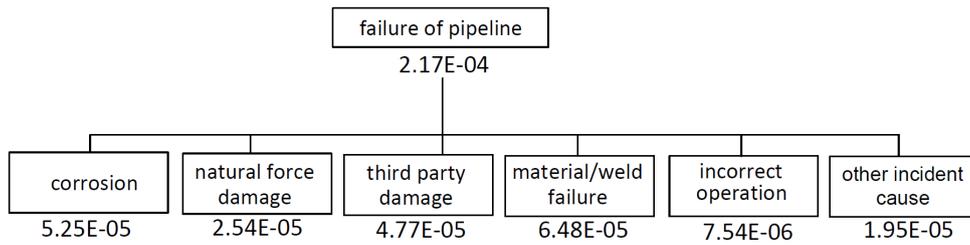


Figure 4: Rate of the occurrence of damage to pipelines

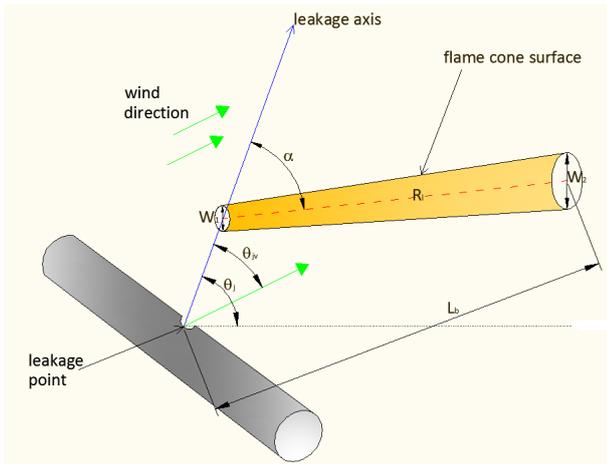


Figure 5: Basic dimensions of the flame

Table 2: Analyzed scenarios

	Scenario 1	Scenario 2	Scenario 3
Gas composition:			
methane, %	100	80	50
hydrogen, %	—	20	50
Initial parameters:			
pressure, bar	16/70	16/70	16/70
temperature, °C	15	15	15
Atmospheric conditions:			
wind speed, m/s	1.5	1.5	1.5
air temperature, °C	20	20	20
humidity, %	88	88	88

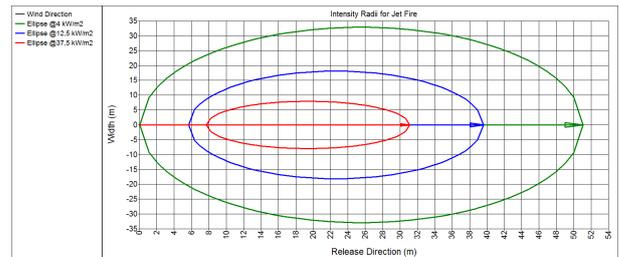


Figure 6: Hazard zones related to methane jet fire

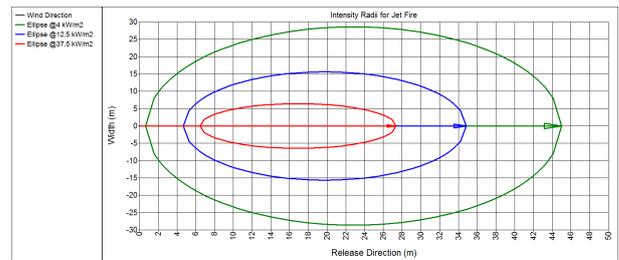


Figure 7: Hazard zones related to methane/hydrogen mixture jet fire

As mentioned earlier, the general practice in Western European countries to date has been to use hydrogen/natural gas mixtures with the hydrogen content not exceeding 5%. However, higher hydrogen content is assumed in ongoing and planned testing. In further considerations, comparative analyses are conducted assuming an uncontrolled release of mixtures with varying proportions of the component gases. The analyzed scenarios are described in Table 2 below. The values of pipeline gas pressure are taken in relation to the following categorization in Poland [19]:

- low-pressure pipelines (up to 10 kPa)
- medium-pressure pipelines (10 kPa to 0.5 MPa)
- raised-pressure pipelines (0.5 MPa to 1.6 MPa)
- high-pressure pipelines (> 1.6 MPa).

Fig. 6 and Fig. 7 present ranges of hazard zones with a specific level of heat flux (exceeding 37.5, 12.5 and 4 kW/m²) assuming scenarios 1 and 2. The pipeline dimensions adopted for the analysis are: d = 100 mm and L = 10 km. The pipeline suffered major damage, and the methane/mixture parameters are: p = 16 bar and t = 15 °C. The presented results are obtained using PHAST v6.7 software, which makes use of the Chamberlain model discussed earlier [15, 20]:

Analyzing the charts presented above it can be noticed that adding hydrogen to methane results in a reduction

in the range of hazard zones. The zone with the most dangerous level of thermal radiation for humans—causing death—covers a range of about 30 meters. The hazard presented to humans and property depends on the degree of pipeline damage and, consequently, on the volume of release. Fig. 8 and Fig. 9 present example charts illustrating time-dependent changes in the mass outflow of natural gas and the hydrogen/methane mixture from a 20 km long pipeline with the diameter of 150 mm. The gas pressure and temperature are p = 70 bar and t = 15 °C, respectively. Fig. 8 relates to major damage to the pipeline, whereas Fig. 9—to moderate damage (the gas flows out through a lo-

cal puncture). The ratio between the hole and the pipeline cross-section surface areas is $a = 0.2$ [20]. It can be seen that the mass outflow is higher for methane than for the methane/hydrogen mixture.

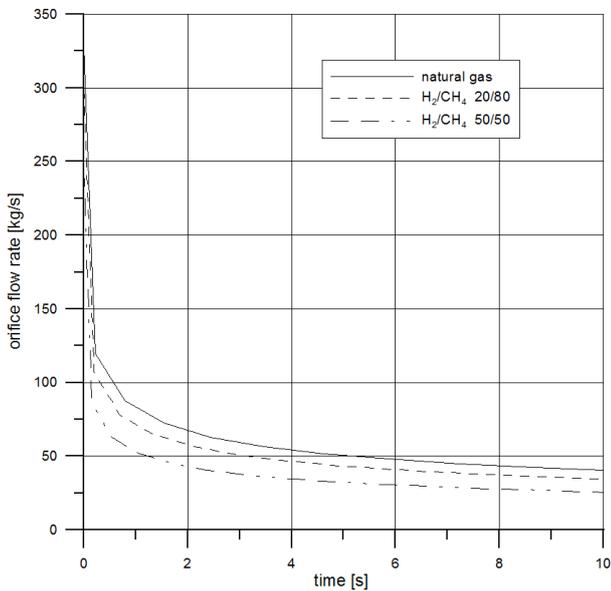


Figure 8: Mass flow of released substance depending on time—full-bore rupture

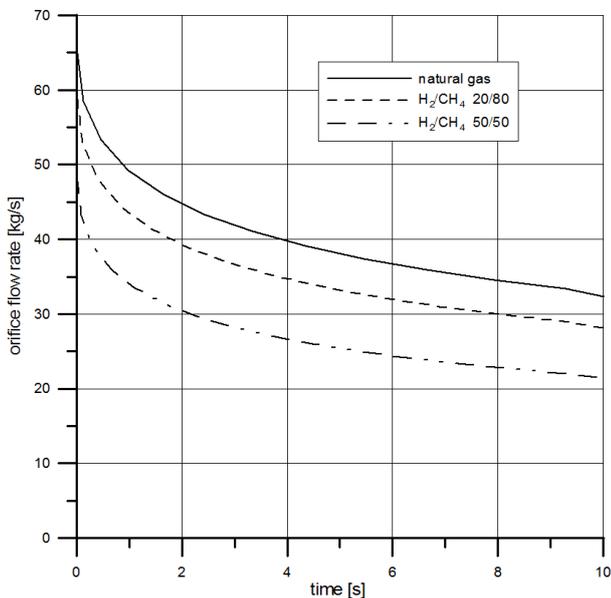


Figure 9: Mass flow of released substance depending on time—puncture damage

The figures below present example values of the heat flux estimated for the jet fire of the gas mixtures under analysis. The charts presented in Fig. 10 and Fig. 11 relate to analyses assuming the same parameters as in Fig. 8–9 [20]. The high level of thermal radiation dangerous for humans and property (exceeding 37.5 kW/m^2) will prevail within a distance of 90 m in the case of a full-bore rupture and within

about 70 m if puncture damage occurs.

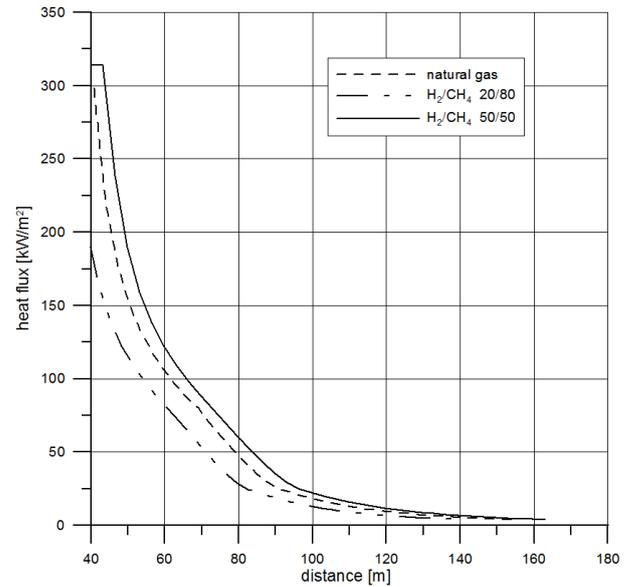


Figure 10: Heat flux depending on the distance from the fire (full-bore rupture)

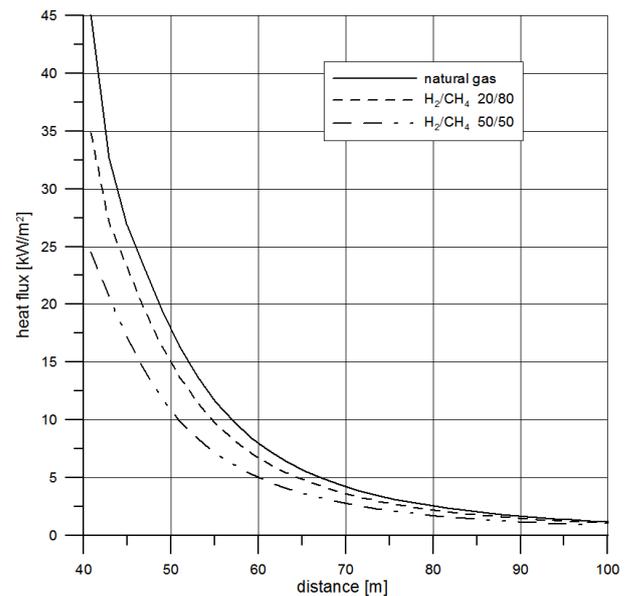


Figure 11: Heat flux depending on the distance from the fire (puncture damage)

The hazard level related to the uncontrolled release and jet fire depends on the amount of gas released and the gas parameters in the pipeline. Fig. 12 presents the dependence of heat flux on the distance from the fire site for a 20 km long pipeline with diameter of 150 mm. The parameters of the natural gas and the hydrogen/methane mixture in the pipeline are as follows: temperature— 15°C , pressure—16 bar. The chart relates to moderate (puncture) damage to the pipeline [20]. It can be noticed that the heat flux arising due to the jet fire is almost 80% lower if the gas pres-

sure is lowered. The hazard zone for the thermal radiation level exceeding 37.5 kW/m^2 will cover a range of about 42 m from the fire site.

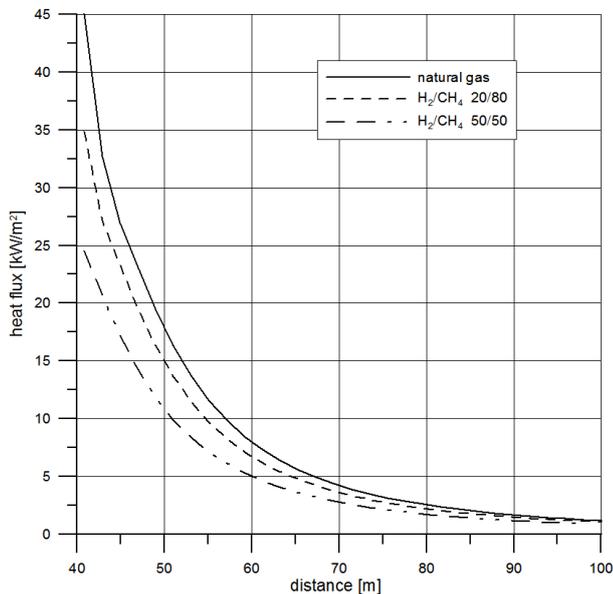


Figure 12: Heat flux depending on distance from the fire site (puncture damage to the pipeline)

The gas network pipelines are characterized by different parameters of transported medium and different diameters. Figure 13 presents changes in heat flux arising at a distance of 50 m from the jet fire site depending on the change in pipeline diameter. The presented analysis concerns a 20 km long pipeline with moderate damage transporting gas at 16 and 70 bar.

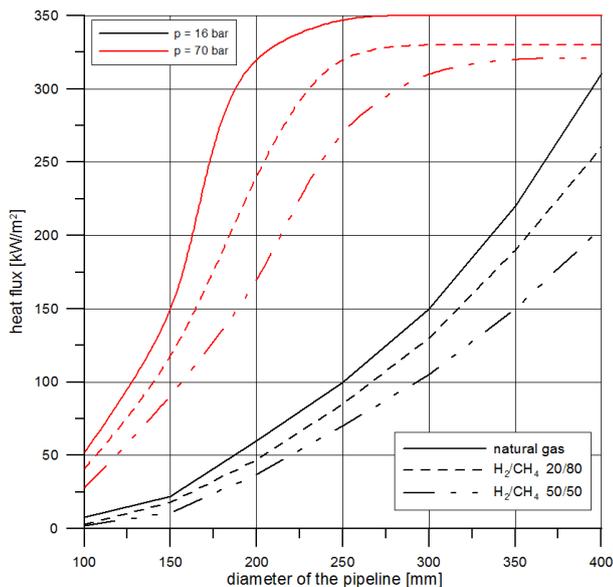


Figure 13: Heat flux depending on distance from the fire site (puncture damage to the pipeline)

Analyzing all the charts presented above, it can gener-

ally be noticed that if a fire occurs, higher hydrogen content in the existing gas network may result in less extreme effects of failure. The hazard zones arising due to the heat flux generated by the flame are smaller if hydrogen is added to natural gas. However, it should be remembered that due to its physiochemical properties, hydrogen has a considerable impact on the mechanical strength of pipelines, thereby increasing their failure rate. This involves a greater probability of pipeline damage and, as a result, greater risk.

5. Conclusions

Undoubtedly, hydrogen is a significant energy carrier. The testing related to gas production, use, storage, and transport to end users constitutes a wide area of research taken up by numerous scientific centers. The testing concerns technical issues relating to the construction of dedicated hydrogen infrastructure or the use of existing facilities. These types of considerations are driving intensive research into the possibility of adding hydrogen to the existing natural gas network and transporting the mixture. Such an adaptation would enable a substantial reduction in investment costs related to implementing hydrogen into the wider fuel system. It has to be remembered that the research works should also comprise the aspects of safety since hydrogen's physiochemical properties may have a significant impact on the overall reliability of the gas network. If hydrogen is added to the natural gas network it will lead to enhanced weakening of the mechanical strength of steel and a higher probability of corrosion. This paper presents the effects of failure caused by pipeline damage. The analyses concern the consequences of an uncontrolled release and jet fire of methane and of a methane/hydrogen mixture. The fire following a release of gas from a pipeline under high pressure generates high thermal radiation, which creates a hazard for humans and property. Depending on the gas parameters and the pipeline dimensions, the hazard zone can cover a range of about 70 meters. The zone gets smaller if the gas pressure is lowered or if the pipeline diameter is reduced. Although the fire-related hazards of the methane/hydrogen mixture are smaller compared to the fire of pure methane, the total risk related to transport of the mixture may be higher. This is due to the fact that the probability of damage to pipelines transporting the CH_4/H_2 mixture may be higher.

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