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# Analysis of pipeline transportation systems for carbon dioxide sequestration

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**Abstract** A commercially available ASPEN PLUS simulation using a pipe model was employed to determine the maximum safe pipeline distances to subsequent booster stations as a function of carbon dioxide ($CO_2$) inlet pressure, ambient temperature and ground level heat flux parameters under three conditions: isothermal, adiabatic and with account of heat transfer. In the paper, the $CO_2$ working area was assumed to be either in the liquid or in the supercritical state and results for these two states were compared. The following power station data were used: a 900 MW pulverized coal-fired power plant with 90% of $CO_2$ recovered (156.43 kg/s) and the monothanolamine absorption method for separating $CO_2$ from flue gases. The results show that a subcooled liquid transport maximizes energy efficiency and minimizes the cost of $CO_2$ transport over long distances under isothermal, adiabatic and heat transfer conditions. After $CO_2$ is compressed and boosted to above 9 MPa, its temperature is usually higher than ambient temperature. The thermal insulation layer slows down the $CO_2$ temperature decrease process, increasing the pressure drop in the pipeline. Therefore in Poland, considering the atmospheric conditions, the thermal insulation layer should not be laid on the external surface of the pipeline.

**Keywords:** Carbon dioxide; Dense phase; Pipeline transportation; Energy efficiency; Thermal insulation

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# 1 Introduction

Of several approaches to carbon dioxide ($CO_2$) transport, pipeline transportation is the most economical one to transport large amounts of $CO_2$ over long distances. Zhang *et al.* [18] studied the pressure drop behavior of supercritical $CO_2$ as well as the $CO_2$ dense phase along the pipeline. Their results show that the pressure along the pipeline keeps dropping until $CO_2$ evaporates and the pipeline may eventually be blocked. This means that there is a maximum safe transport distance. If there is a need to transport $CO_2$ farther than over this maximum distance, boosting pump stations are needed along the pipeline. The $CO_2$ can be transported over long distances in two states: either as a supercritical fluid or as a subcooled liquid. Gas-phase transport is disadvantageous due to the low density and high pressure drops. Generally, $CO_2$ transportation in the subcooled liquid state has some advantages over the supercritical state transport, most importantly because of the lower compressibility and higher density of the liquid within the pressure range considered here, which permits smaller pipe sizes and generates lower pressure losses. In the present work, the state of existence of $CO_2$ was assumed to be either in the liquid or in the supercritical state. The aim of this paper is to analyze $CO_2$ transport via a pipeline from the capture site to the disposal site under isothermal, adiabatic and heat transfer conditions. According to the conclusions reached at [18], the currently available versions of the equations of state (EOS) to predict properties of supercritical $CO_2$ under conditions close to the critical point are not reliable enough to design a precise compression system. In the present work, in order to compare the results, two Lee-Kesler-Plocker (LKP) and Peng-Robinson-Boston-Mathias (PRBM) equations of state were used. In the following discussion, the same power station data as those reported in [4, 9] were assumed. ASPEN PLUS V 7.0 [2], a commercially available design process simulator with an extensive thermodynamic library, was used to simulate the $CO_2$ transportation process. The calculations were carried out assuming pure carbon dioxide. However, captured $CO_2$ does include a series of impurities depending on the capture technology which affects the $CO_2$ phase diagram. Moreover, in real pipeline transportation of $CO_2$, the pipeline may go through changes in elevation, which has not been considered until now. But it has to be noted that a change in elevation has a great impact on the hydrodynamic performance. This work can be used as reference for the design and construction of $CO_2$ pipelines in Poland in the future.

## 2 Physical properties of carbon dioxide

The properties of carbon dioxide are considerably different from those of other fluids commonly transported by pipeline. Thus, in pipeline design, it is necessary to use accurate representations of the phase behavior, density, and viscosity of pure $CO_2$ and of $CO_2$ containing impurities. For the multiphase flow, models or correlations are currently available for predicting the pressure profile in a well. An important characteristic of $CO_2$ that distinguishes it from other substances typically bulk-transported in pipelines is its low critical temperature, namely 31.1 °C. Technically, $CO_2$ can be transported through pipelines as a gas, as a supercritical fluid or as a subcooled liquid, depending on the pressure and temperature conditions in the pipeline system (Fig. 1). Since $CO_2$ is a highly corrosive medium, the water content must be reduced to less than 60% of the saturation state [6]. In the case of intercooled compression, a portion of the moisture is removed through condensation. However, it is still necessary to provide a further drying stage after the final compressor stage.

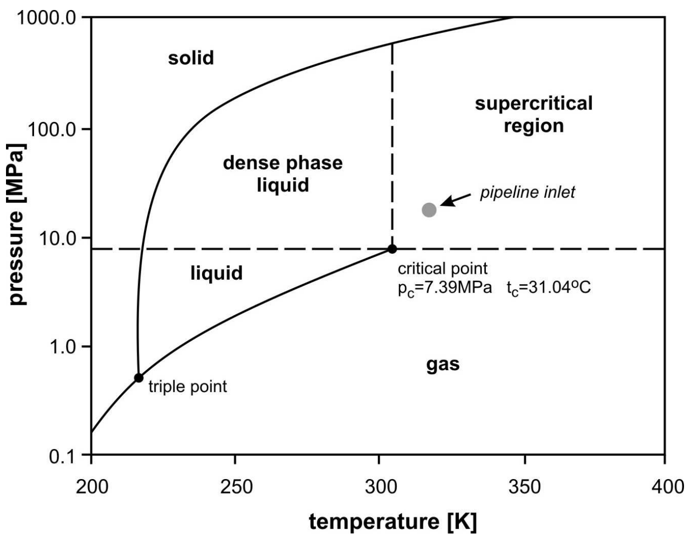


Figure 1. A phase diagram for $CO_2$.

The method of controlling the system temperature and pressure under a particular condition directly determines significant aspects of the design of the system processes, the pressure losses, the mechanical structure and, ultimately, the energy and cost efficiency. The results presented in this paper

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are based on the physical properties of $CO_2$ containing impurities and were obtained using real gas equations of state (EOS) with the Lee and Kesler equation modified by Plocker, Knapp, and Prausnitz (the LKP equation of state) [2,8] and the Peng-Robinson equation of state with Boston-Mathias modifications (PRBM) [2,14]. All these equations are included in the ASPEN PLUS V 0.7 design process simulator [2].

Moreover, Fig. 2 shows that $CO_2$ compressibility is nonlinear in the range of pressures common for pipeline transport and is highly sensitive to any impurities as predicted by the Peng-Robinson equation of state [10]. Thus, it is necessary to use accurate representations of the phase behavior, density, and viscosity of $CO_2$ while designing a pipeline. To reduce difficulties in design and operation, it is generally recommended that the pressure in a $CO_2$ pipeline should be higher than 8.6–10 MPa because the abrupt changes in $CO_2$ compressibility can then be avoided across the range of temperatures that may be encountered in the pipeline system [5,10].

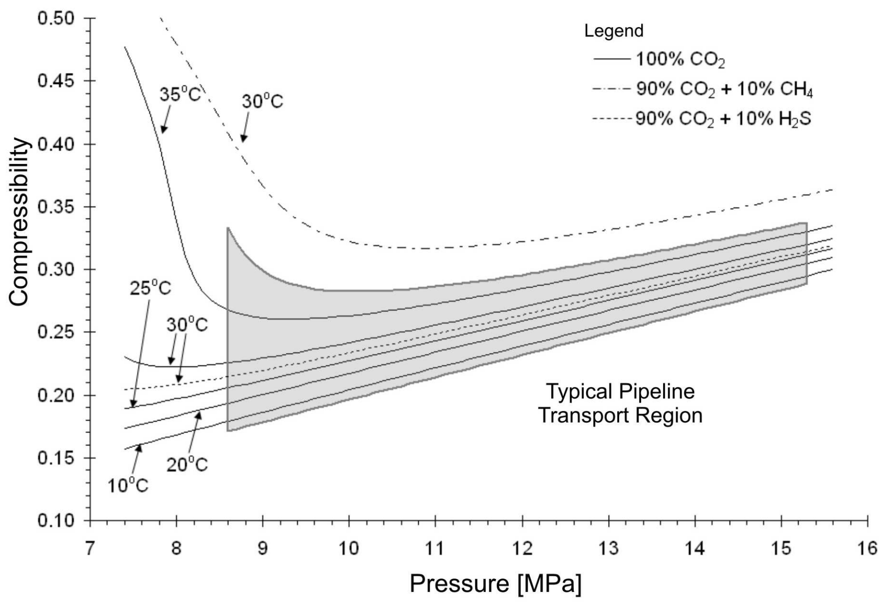


Figure 2. Nonlinear compressibility of $CO_2$ in the range of pressures common for pipeline transport as predicted by the Peng-Robinson equation of state [10].

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## 3 Pipeline configuration

A complete $CO_2$ capture and sequestration (CCS) system requires safe, reliable and cost-efficient solutions for transmission of $CO_2$ from the capturing facility to the permanent storage site. The $CO_2$ pipeline facilities from the power plant flue stack, through the separation, compression, transportation and pumping systems to the injection well head are shown schematically in Fig. 3. For sequestration purposes, $CO_2$ is generally injected to depths exceeding 1000 m [11]. At greater depths, $CO_2$ increases in density and below 800 m it becomes a supercritical fluid. A large compressing system is required to compress the source $CO_2$ under nearly atmospheric pressure conditions. Figure 3 provides an example of an eight-stage integrally geared compressor system, which was selected in [16] as the most available, reliable and efficient compression technology and injection configuration. Compressor stations in a $CO_2$ pipeline system can be subdivided into two classes: stations positioned at the pipeline inlet, and booster stations located along the pipeline to compensate for the pressure drop due to friction and elevation losses.

## 4 Properties of $CO_2$ in pipeline transport

After $CO_2$ is captured at emission sources, it has to be transported to the storage site. At present, pipelines are the most common means of transportation of large quantities of the gas. Two states can be used to transport $CO_2$ over long distances: either as a supercritical fluid or as a subcooled liquid. The physical condition which is suitable for pipeline transportation in terms of pressure and temperature, is the supercritical/dense phase. This phase is preferable due to the fact that it is relatively stable compared to the liquid state, which minimizes cavitation problems in the system components such as booster stations and pumps. Since the critical point for $CO_2$ is 31.1 °C and 7.38 MPa, the system pressure higher than 7.5 MPa results in transportation at supercritical parameters, as long as the temperature remains above 31.1 °C. According to Fig. 1, if pressure drops below the critical pressure, the phase may be liquid or gaseous, or both, depending on the local temperature. Gas-phase transport is disadvantageous due to the low density and the high pressure drop. Since critical temperature is higher than normal ground temperature, either thermal insulation is needed to keep $CO_2$ in the supercritical state or $CO_2$ needs to be heated at every

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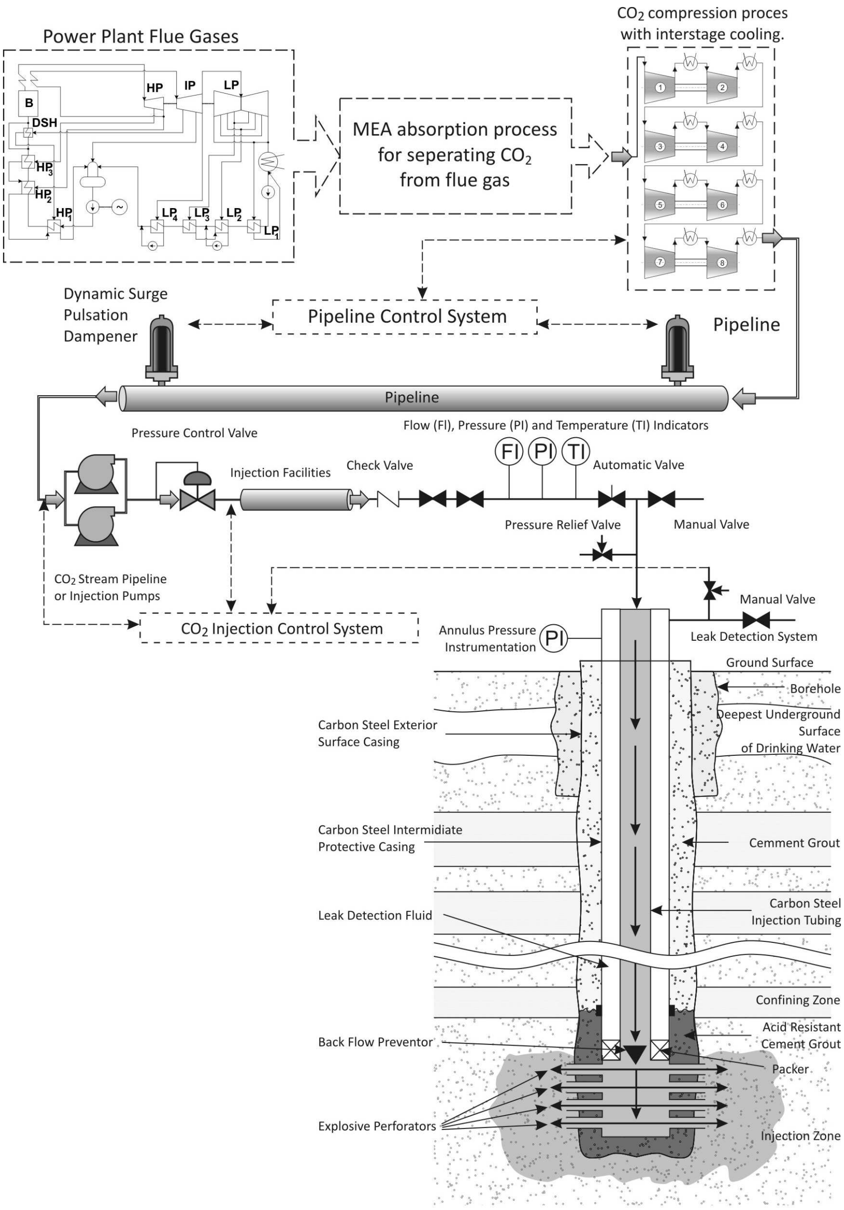


Figure 3. Diagram of a $CO_2$ pipeline transportation configuration (processing, compression, and injection). B-boiler, HP-high pressure part, LP-low pressure part, IP-intermediate pressure part of the steam turbine, LP1, LP2, LP3, LP4 low pressure feed water heater, HP1, HP2, HP3-high pressure feed water heater, DSH-desuperheater.

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certain distance. Otherwise, it will transform into the liquid state. Meanwhile, some authors propose that transporting liquid $CO_2$ at a relatively low temperature is preferred in terms of a reduction in the pressure drop along the pipeline [19]. In the present paper the $CO_2$ working area is assumed to be either in the liquid or in the supercritical state and the results of these two states are compared.

For subcooled liquid $CO_2$ transportation, a facility cooling $CO_2$ to 15 °C or less is needed so that it can be kept below its critical temperature down the line. Conceptually, refrigeration could be added along the pipeline using $CO_2$ as the working medium, but this will obviously increase the capital and operating costs as well as reduce the overall energy efficiency. Generally, $CO_2$ transportation in the subcooled liquid state has some advantages over the supercritical state transport, most importantly because of the liquid lower compressibility and higher density within the pressure range considered here, which permits smaller pipe sizes and generates lower pressure losses. To reduce difficulties in design and operation, it is generally recommended that the pipeline should operate at pressures higher than 8.6 MPa. Then, the abrupt changes in $CO_2$ compressibility and specific heat can be avoided across the range of temperatures (Fig. 2) that may be encountered in the pipeline system [5,10].

Most new pipelines are laid underground, despite the higher initial costs, for environmental, security and safety reasons. Underground temperatures are much more stable than surface temperatures. Hence the operating temperatures of $CO_2$ pipelines are generally dictated by the temperature of the surrounding soil.

The pressure keeps dropping along the pipeline until $CO_2$ evaporates and the pipeline may eventually be blocked. This means that there is a maximum safe transport distance. If there is a need to transport $CO_2$ farther than over this maximum distance, boosting pump station are required along the pipeline.

A pipeline segment is defined as a length of pipeline for which the inlet pressure and the minimum outlet pressure values are specified, e.g., a length of pipeline between two compressor stations.

## 5 Pressure loss correlation

There are a number of fluid correlations, derived empirically, that account for the hydrostatic and frictional fluid losses in a wellbore under varied flow conditions. The presence of a multiphase flow greatly complicates pressure drop calculations. Many flow models or correlations are currently available for the multiphase flow making it possible to predict the pressure profile in a well. The reasonably good performance of multiphase flow models, within the context of [10], is considered to be burdened with a relative error, between the measured and predicted values of the pressure profile, which is less than or equal to 20%. The Beggs and Brill method [3] is suitable for the multiphase flow and for the horizontal or vertical flows as well as intermediate cases. It also takes account of the general mechanical energy balance and the average *in situ* density to calculate the pressure gradient.

# 6 Modeling $CO_2$ transport by pipeline for the case study

In the following discussion, the same power station data as those reported in [4,9] are used. They include: a 900 MW pulverized hard coal-fired power plant with 90% of $CO_2$ recovered and the MEA (monoethanolamine) amine based absorption method for separating $CO_2$ from the flue gases. The transport mass flow rate was assumed at 4.93 Mt/year (156.43 kg/s) and the distance – at 400 km. The pipeline inlet pressure was assumed to be 153 MPa, and the inlet temperature – 35 °C at the supercritical state. Once the $CO_2$ pressure drops to below 9 MPa, a boosting station would be installed to increase the pressure back to 153 MPa. The pipeline need not be insulated when advantage can be taken of cold ground conditions, which helps to maintain liquid conditions. The typically long length of a $CO_2$ pipeline segment coupled with the lack of insulation on buried pipelines can be treated as an isothermal system, where $CO_2$ features the temperature of the earth surrounding the pipeline. Considering that the flow velocity of $CO_2$ inside the pipeline is usually between 1 and 2 m/s, an internal diameter of 0.45 m was assumed based on a trial and error calculation.

The pipe wall thickness, $t$, in meters is given as [13]

$$t = \frac{p_{mop}\, d_2}{2\, S\, E\, F}\,, \tag{1}$$

in which $p_{mop}$ is the maximum operating pressure of the pipeline (Pa), $d_2$ is the outside pipe diameter (m), $S$ is the specified yield stress for the pipe material (Pa), $E$ is the longitudinal joint factor, and $F$ is the design factor.

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For the purpose of estimating the pipe wall in this case study, the maximum operating pressure is assumed at 153 MPa, the longitudinal joint factor is 1.0, and the design factor is 0.72 (US Code of Federal Regulations – CFR, [13]). The minimum yield stress is specified as 483 MPa, which corresponds to the API (American Petroleum Institute) for 5L X-70 steel line pipe [1]. Alternatively, a thermal insulation layer was assumed on the pipeline external surface. The flow process of $CO_2$ along the pipeline is mainly influenced by three factors: friction forces, heat exchange through the pipe wall between the soil and the thermal insulation layer, and the change in elevation. Based on the data given above, thickness of the pipe wall, $t$, was calculated to be 10 mm. Since the critical temperature of $CO_2$ is predominately higher than the normal temperature of the soil or the ambient temperature, after $CO_2$ is compressed and boosted to above 10 MPa, the thermal insulation will slow down the $CO_2$ temperature decrease process, increasing the pressure drop in the pipeline. Therefore, the thermal insulation layer should not be laid on the pipeline external surface in Poland. In the present work, the $CO_2$ working area was assumed to be either in the liquid or in the supercritical state.

# 7 Results and discussion

## 7.1 Comparison between adiabatic and isothermal transmission

### 7.1.1 Maximum safe transport distance

For fluid flow through pipelines, the transmission process can be generally found between isothermal and adiabatic conditions. For typical lengths of the underground $CO_2$ pipeline segment with no insulation, the segment may be treated as an isothermal system, where $CO_2$ is at the temperature of the soil surrounding the pipeline. If $CO_2$ enters the pipeline in the supercritical state, it goes into the gaseous state at some point along the pipeline because of the pressure drop. At a constant diameter pipeline, the $CO_2$ velocity increases along the pipeline, causing a very big pressure drop or 'choking conditions' at a certain distance.

Figure 4 shows a comparison of the pressure drop and the fluid density change resulting from it depending on the distance for different initial $CO_2$ temperature values, for adiabatic and isothermal flow conditions. There is not much difference between the adiabatic and isothermal conditions when

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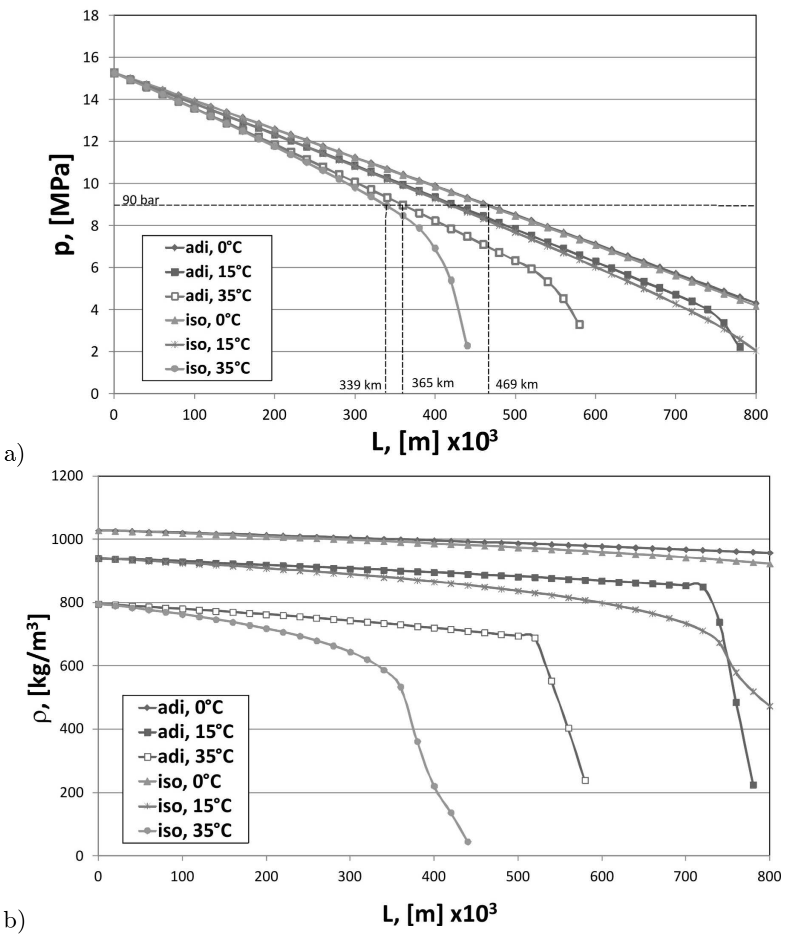


Figure 4. Comparison of the pressure drop (a) and density changes (b) along the pipeline for adiabatic and isothermal conditions at different inlet $CO_2$ temperatures.

$CO_2$ at the inlet is in the liquid state because the liquid is incompressible. It also shows that a negligible difference exists between adiabatic and isothermal transmission when the $CO_2$ inlet state is liquid at 15 °C. The difference becomes significant when $CO_2$ reaches the supercritical fluid state (35 °C). Under isothermal conditions and with an initial subcooled liquid, there is a sufficient heat transfer to the ground, and, therefore, the transmission distance is shortened. In adiabatic conditions, there is no heat transfer across the pipe wall and the transmission distance is longer. As it was accepted earlier, the lowest transport pressure of the $CO_2$ pipeline is 9 MPa. In this

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case, the maximum safe transport distance depends on the thermal conditions, changing from 469 km at the $CO_2$ subcooled temperature of 0 °C to 339 km at the supercritical temperature of 35 °C, and under isothermal conditions. For the adiabatic case, there is a discontinuity in the density profile. This discontinuity corresponds with the saturation state when $CO_2$ changes density quickly, e.g., from the subcooled liquid state to a two-phase state. Even for supercritical fluids where there is no phase change, the density variation has a very nonlinear region. With initial temperatures above the supercritical point, the $CO_2$ density changes abruptly within the pipeline once the temperature reaches the saturation point, and reaches two-phase flow conditions. Moreover, Fig. 4 also indicates that if the inlet temperature is higher than critical, $CO_2$ repressurization is needed after a much shorter distance, whether adiabatic or isothermal conditions prevail.

#### 7.1.2 Influence of the pipe diameter

The pipeline diameter is incorporated as a crucial parameter in the cost estimation of $CO_2$ pipeline transport. Figure 5 shows the maximum safe transport distance of $CO_2$, (a) and the influence of different internal pipe diameters under adiabatic and isothermal conditions on $CO_2$ density (b), and velocity (c). Actually, as it was assumed earlier, the lowest transport pressure is 9 MPa. In this case, the maximum safe transport distance is 110 km, 220 km, and 405 km at the pipe inner diameters of 0.35 m, 0.4 m, and 0.45 m, respectively. It can be seen from Fig. 5 that the inner diameter of the pipeline has a strong influence on the number of boosting pump stations in the long distance transport and, consequently, on the total pipeline transportation costs.

### 7.2 Energy balance with surroundings

#### 7.2.1 General remarks

Analysis of $CO_2$ transport by pipeline must take a most realistic account of the influence of the ambient temperature on heat exchange between carbon dioxide in the pipe and the surroundings along the pipeline. Some studies proposed that $CO_2$ should be transported in the supercritical state. For a subcooled liquid transmission and a temperature higher than critical to minimize heat gains, the pipeline may be placed underground and/or insulated. An underground and insulated pipeline reduces the pressure drop and, therefore, the energy losses in the system. However, this results in

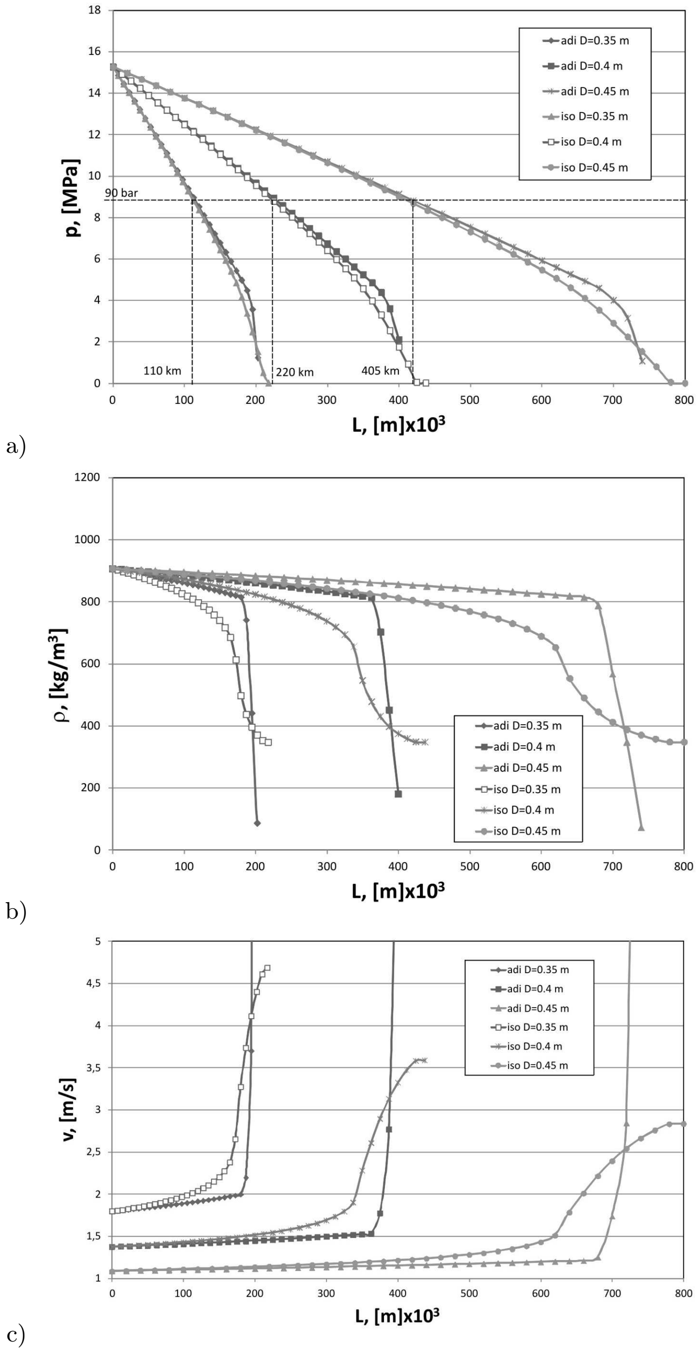


Figure 5. Maximum safe transport distances (a), density (b) and velocity (c) with different internal pipe diameters in adiabatic and isothermal conditions.

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the increase in capital and maintenance costs. The pipeline needs not be insulated when advantage can be taken of cold ground conditions, which maintain liquid conditions. In the present work, the $CO_2$ working area was assumed to be either in the liquid or in the supercritical state. In the latter case, thermal insulation was assumed on the external surface of the pipe (Fig. 6). Engineering experience indicates that long distance pipelines are usually placed underground at a depth of 1.2–1.5 m. It is also found that the annual lowest and highest soil temperatures at a depth of 1.5 m in Poland are between 5 and 16 °C (Fig. 7).

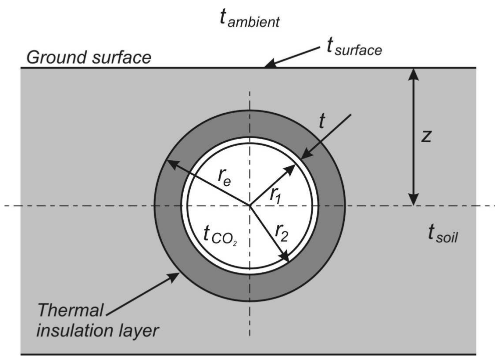


Figure 6. Cross section of the underground and insulated pipeline. $r_1$ – internal radius of pipe, $r_2$ – external radius of pipe, $r_e$ – external wall radius of the thermal insulation layer, $t$ – pipewall thickness, $t_{surface}$ – ground surface temperature, $t_{soil}$ – soil temperature.

Two cases – with the lowest and the highest soil temperatures – are considered in the pipeline design to ensure that the pipeline can operate well over the whole year.

A two-dimensional heat conduction formula [7] can be used to calculate the overall heat transfer coefficient between the ground and the $CO_2$ in the pipeline (Fig. 6):

$$k = \frac{1}{\frac{r_1}{\lambda_{pw}} \ln \frac{r_2}{r_1} + \frac{r_1}{\lambda_{ti}} \ln \frac{r_e}{r_2} + \frac{r_1}{\lambda_{soil}} \ln \frac{2z}{r_e} + \frac{r_1}{z} \frac{1}{\alpha_{ag}}}\,, \tag{2}$$

where heat conductivities of the pipe wall and of the insulation layer materials are $\lambda_{pw} = 25$ W/mK and $\lambda_{ti} = 0.058$ W/mK, respectively.

The thermal conductivity of the soil is assumed at $\lambda_{soil} = 1.21$ W/(mK), and the distance between the ground surface and the pipe center is 1.225 m. The air convection heat transfer coefficient is $\alpha_g = 5$ W/m$^2$K. According

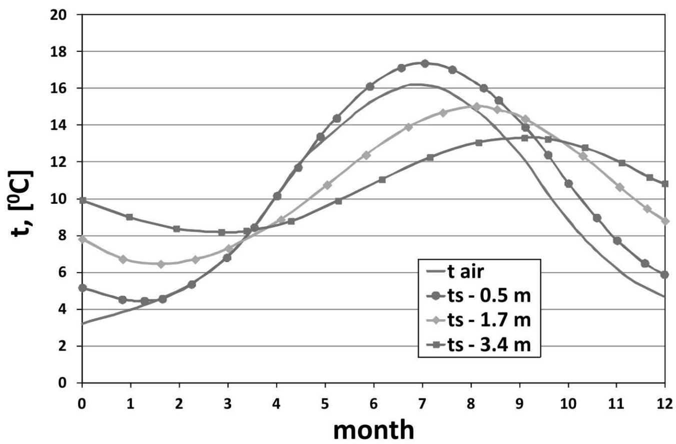


Figure 7. Annual soil temperatures at different depths and ambient temperatures, $t_{soil}$ – soil temperature.

to [18] and [19], the thermal resistance of the convective thermal transfer between $CO_2$ and the inner pipe wall is much smaller than that between the pipe wall and the heat insulation layer, so it is assumed that the temperature of the inner pipe wall is equal to the temperature of $CO_2$ on the same cross section. The value of the overall heat transfer coefficient $k$ between the ground and the $CO_2$ calculated from Eq. (2) for a pipeline with a 0.05 m and 0.03 m heat insulation layer is 0.7387 and 0.912 W/m$^2$K, respectively, and for a pipeline without insulation – 2.11 W/m$^2$K. Resistance to the heat transfer from the tubing and casing is ignored, as the conductivity of the steel used in the tubing and casing is at least an order of magnitude larger than any other conductivity in the system.

### 7.2.2 Choking conditions

An increase in the pressure drop means higher operating costs and possibly the need to introduce compressor stations. The pressure drop along the pipeline is dependent on the flow velocity, ambient temperature, as well as on geometric characteristics of the pipeline such as length, elevation changes etc. The pressure drop and temperature changes along the pipeline reduce the $CO_2$ density and increase velocity, which, in turn, increases the pressure drop and ultimately leads to a choking condition at a certain distance. The maximum safe pipeline length to prevent choking is preliminarily selected at a value about 10% smaller than the choking point [18]. The dependence

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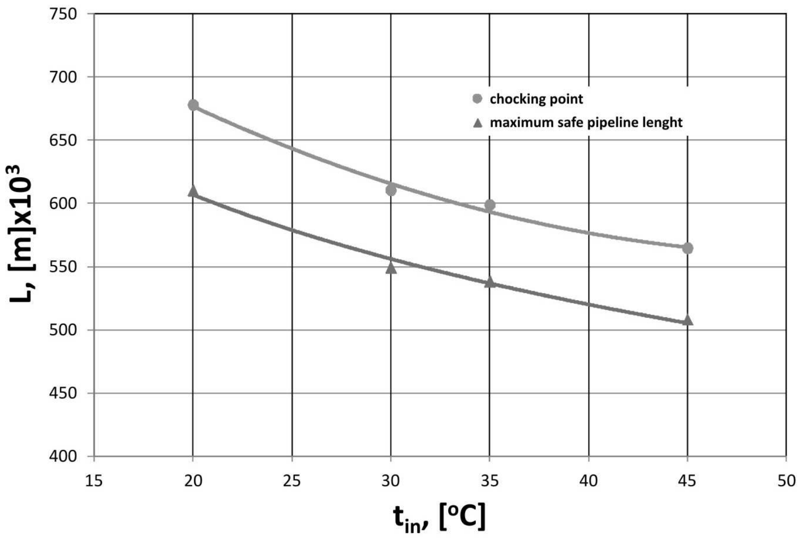


Figure 8. Dependence of the safe pipeline length and of the choking point on $CO_2$ pipe inlet temperatures (20 °C, 30 °C, 35 °C, 45 °C) at energy balance with surroundings.

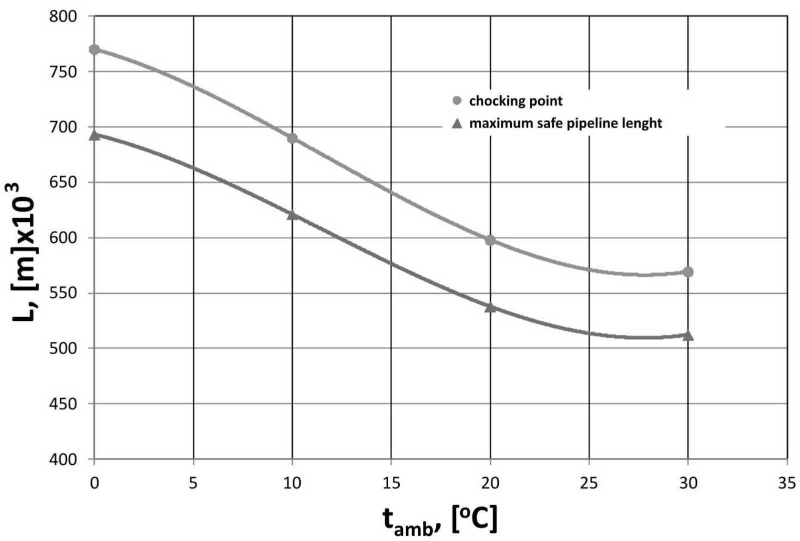


Figure 9. Dependence of the safe pipeline length and of the choking point on ambient temperatures (0 °C, 10 °C, 20 °C, 30 °C).

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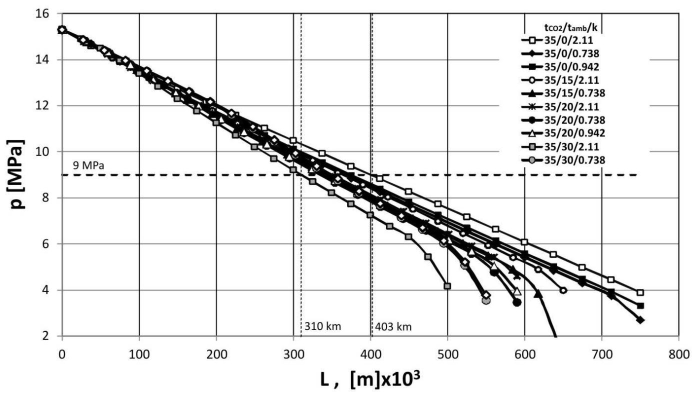
of the safe distance on the pipeline inlet and ambient temperatures for the reference case study is presented in Figs. 8 and 9, respectively. It can be seen that both the $CO_2$ temperature (Fig. 8) and the ambient temperature (Fig. 9) have a significant impact on the pipeline maximum safe length. In order to avoid the choking condition, recompression of $CO_2$ becomes necessary.

### 7.2.3 Influence of ambient temperature and the thermal insulating layer

In order to understand the impact of the thermal insulating layer, the pipeline operational parameters were calculated with and without the insulating layer at different thickness and ambient temperature values. Figures 10 and 11 show four parameters of $CO_2$ (temperature, pressure, density and velocity) along the pipeline with and without insulation, at different ambient temperatures calculated with the use of two different real gas equations of state: the LKP and the RPBM equations. In the simulation, the inlet conditions for $CO_2$ are fixed. It is transported to the injection site in a straight line over flat ground. Figures 10a and 11a show that $CO_2$ pressure drops linearly along the pipeline. It can be seen that the maximum difference in the maximum safe transport distance up to assumed pressure drops to below 9 MPa (about 91 km at the LKP calculations and 78.4 km at the PRBM calculations) occurs for $CO_2$ transmission at maximum differences between ambient temperatures and without thermal insulation.

With initial $CO_2$ temperatures above the supercritical point and with calculations performed using the LKP equations, $CO_2$ density changes abruptly within the pipeline once the temperature reaches the saturation point, and a two-phase flow commences. It can be seen from Fig. 10 that as the ambient temperature gets lower, the liquid phase flow appears at the shorter distance. However, the safe flow distance gets considerably longer. It can be seen that the pressure drop increases significantly with ambient temperature, which confirms our estimation that low temperature is preferable for pipeline transport. It can also be seen from Fig. 9 that as the ambient temperature gets lower, the $CO_2$ temperature drops more quickly to a level lower than the critical point within a very short distance. Figures 12 and 13 show the maximum safe transport distance of the $CO_2$ pipeline at different ambient temperatures with and without thermal insulation layer even more clearly. It can be seen that if the inlet temperature keeps constant, the pressure drop decreases as the ambient temperature decreases

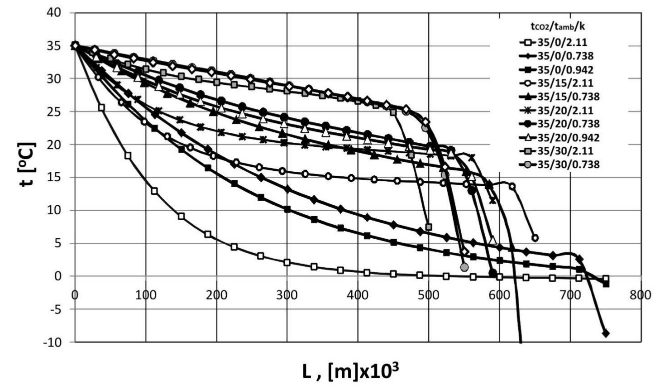


a)

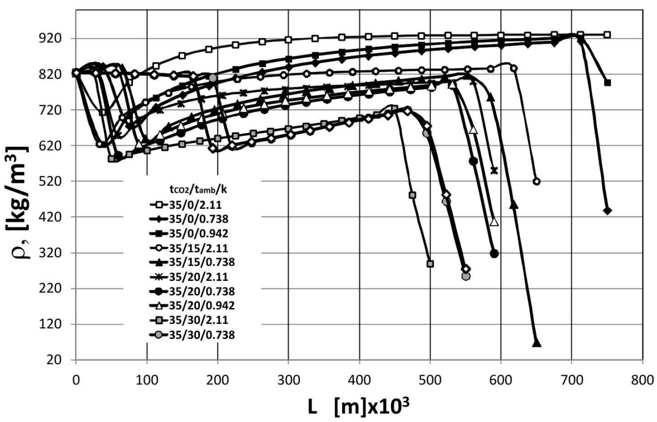
Figure 10. Comparison of the pressure drop (a), the change in temperature (b), in density (c), and in velocity (d) along a pipeline with and without thermal insulation for the conditions of energy balance with surroundings at different ambient temperatures $t_{amb}$: 0°C, 15°C, 20°C, 30°, $t_{CO2}$ – inlet $CO_2$ temperature, $k$ – overall heat transfer coefficient; LKP equation of state.

since velocity then decreases too.

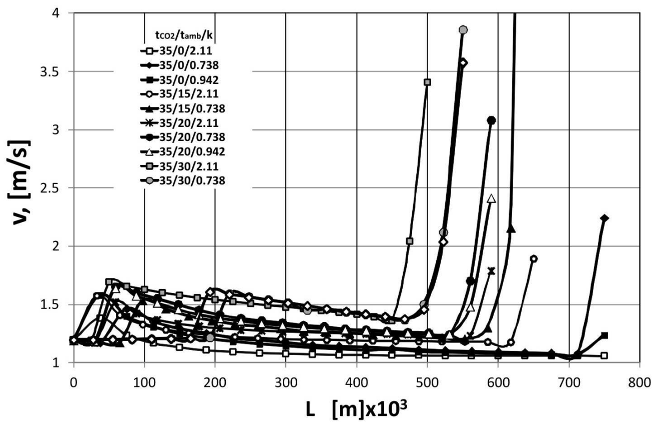
At lower ambient temperatures the pressure drop in the pipeline without thermal insulation is lower than in the insulated pipeline. It can be seen that the maximum difference in the maximum safe transport distance up to assumed pressure drops to below 9 MPa (about 32.8 km both for the LKP and PRBM calculations), for the two cases with and without insulation, occurs for $CO_2$ transmission at the ambient temperature of 0 °C. However, this difference drops to nearly zero as the ambient temperature increases to about 27 °C. Only at the ambient temperature of 30 °C is the safe transport distance longer for the case with insulation if the LKP equations of state are used; the distance obtained by means of the PRBM equations of state is nearly the same. This verifies our estimation that a pipeline without thermal insulation is preferable for pipeline transport in the Polish climate. Generally, safe transportation distances calculated with the use of the PRBM equation of state are longer than those calculated with the LKP equation of state.




b)

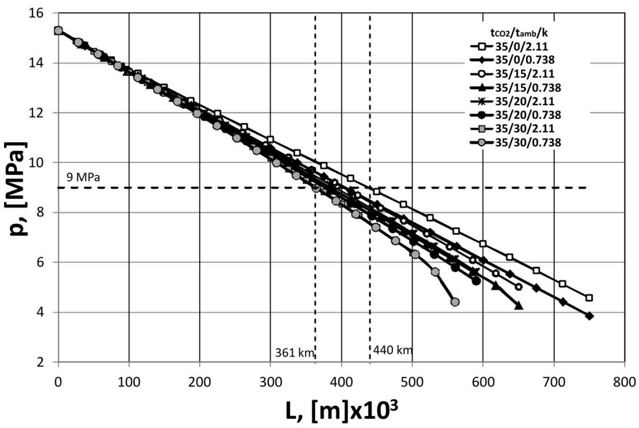



c)

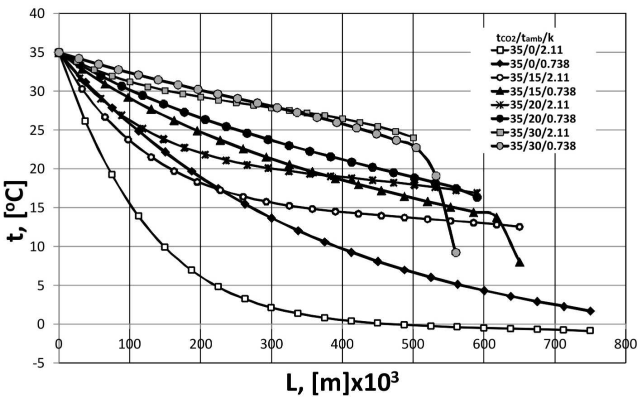



d)

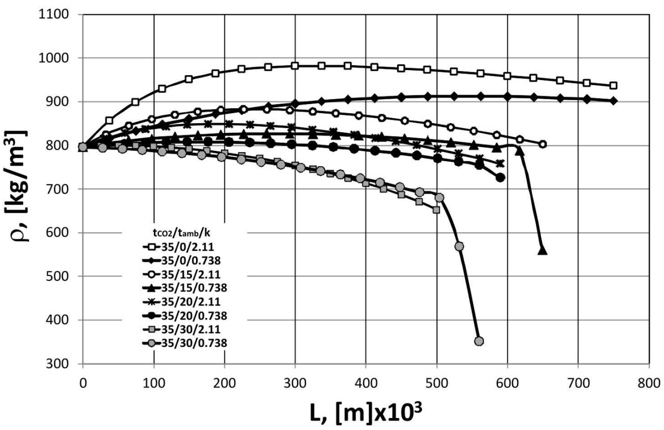
Figure 10b-d (continued).




a)




b)




c)

Figure 11a-c. For caption see next page.

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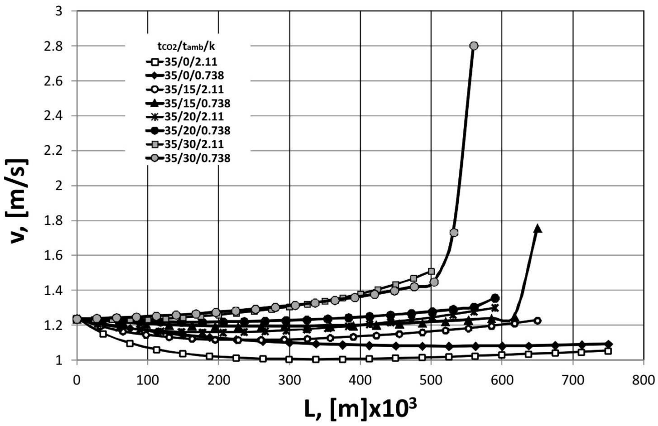


d)

Figure 11. Comparison of the pressure drop (a), the change in temperature (b), in density (c), and in velocity (d) along a pipeline with and without thermal insulation for the conditions of energy balance with surroundings at different ambient temperatures: 0°C, 15°C, 20°C, 30°; PRBM equation of state.

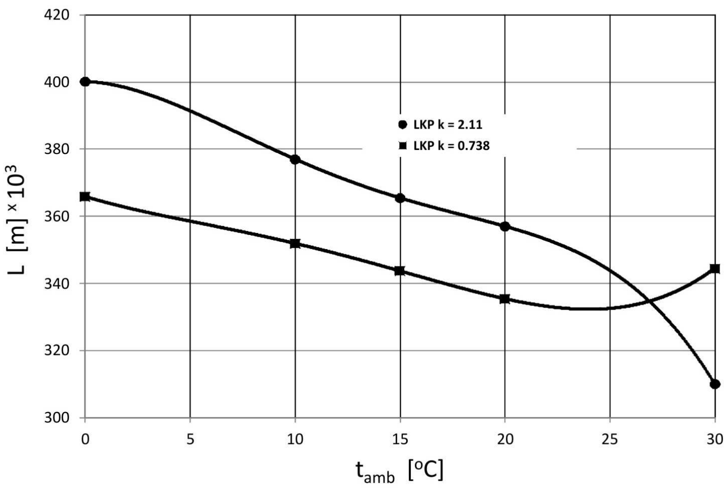


Figure 12. Maximum safe length of a pipeline with ($k = 0.738$) and without ($k = 2.11$) an insulating layer; distance to subsequent booster station at different ambient temperatures; LKP equation of state.

# 8 Conclusions

The paper presents the analysis of the influence of multiple factors, including pipe diameter, pipeline inlet temperature, ambient temperature or thermal

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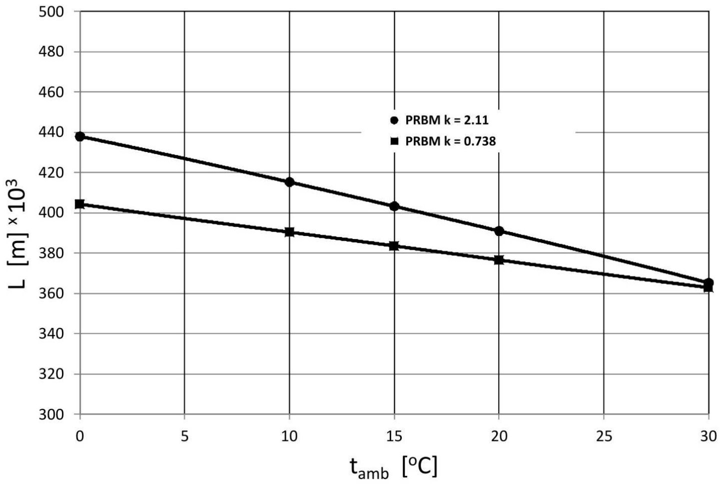


Figure 13. Maximum safe length of a pipeline with and without an insulating layer; distance to subsequent booster station at different ambient temperatures; PRBM equation of state.

insulation layer on the thermodynamic performance of the $CO_2$ flow in the pipeline, and proposes common guidelines for the design of $CO_2$ transport pipelines in terms of the pressure drop minimization, such as the choice of a proper pipe diameter, the necessity to use or not the thermal insulation layer on the external surface of the pipe in the Polish atmospheric conditions and the reduction in the transport temperature. To mitigate difficulties in design and operation, in this case $CO_2$ pipelines are operated at a pressure greater than 9 MPa or under dense phase conditions, where abrupt changes in $CO_2$ compressibility can be avoided across the range of temperatures that may be encountered during the pipeline system operation. The results show that the pressure along the pipeline keeps dropping until $CO_2$ evaporates and the pipeline may eventually be blocked. This means that there is a maximum safe transport distance. If $CO_2$ should be transported farther than the maximum distance, boosting pump stations are needed along the pipeline.

Booster stations are placed at discrete step intervals and their number and the cost they involve may be minimized by a careful analysis. Three transportation conditions – adiabatic, isothermal and with heat exchange between $CO_2$ and the surroundings along the pipeline – were considered. In the analysis of adiabatic and isothermal energy losses, at the lowest final transport pressure of 9 MPa and at the highest initial $CO_2$ temperature of 35 °C, the maximum safe transmission distance to a booster station amounts to 365 km under adiabatic conditions, which is by up to 7.7% longer compared to the distance under isothermal conditions (339 km).

The most realistic approach in the analysis of $CO_2$ transport by pipeline must take account of the influence of ambient temperature on the heat exchange between $CO_2$ and the surroundings along the pipeline. An increase in ambient temperature reduces $CO_2$ density and increases the velocity along the pipeline, which in turn increases the pressure drop and leads to building up choking conditions. A bigger pressure drop means higher operating costs and possibly the need to introduce recompression stations. For the purposes of this study, the maximum value of ambient temperature, which in Poland may be as high as 30 °C, was assumed. This significantly shortens the maximum distance at the inlet pressure of 15.3 MPa to 310 km, compared to the maximum safe distance, which amounts to 403 km at the ambient temperature of 0 °C. So, for a $CO_2$ stream in the inlet supercritical state (35 °C), the maximum safe transmission distance is 310 km, which is by up to 9.3% shorter than the distance calculated for isothermal conditions. To sum up, when designing the pipeline, the extreme case with the highest ambient temperature should be considered to ensure that the pipeline can work well all through the year. For a $CO_2$ stream in the inlet supercritical state (35 °C), the maximum safe transmission distance is 310 km.

Since $CO_2$ temperature is usually higher than the soil temperature after $CO_2$ is compressed and boosted to above 15 MPa, the thermal insulation layer will slow down the $CO_2$ temperature decrease process, increasing the pressure drop in the pipeline. Therefore in Poland, considering the atmospheric conditions, the thermal insulation layer should not be laid on the external surface of the pipeline.

The calculations were carried out assuming pure carbon dioxide. However, captured $CO_2$ includes a series of impurities depending on the capture technology which affects the $CO_2$ phase diagram. Even small amounts of impurities in $CO_2$ change the location of the supercritical line so larger margins of safety may have to be applied in $CO_2$ pipeline design.

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velopment of a Technology for Highly Efficient Zero-Emission Coal-Fired Power Units Integrated with $CO_2$ Capture).

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