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Synergy of S-CO_2 Power Cycle and CCS Systems

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ABSTRACT

Supercritical carbon dioxide (S-CO_2) cycles are currently researched for many applications ranging from nuclear energy through geothermal, solar and waste heat recovery systems. One of the major issue of their development is the design of compressor and heat exchangers close to the critical point. In addition, in the real operation carbon dioxide will not be pure and some impurities will be always present. Similar issues are currently faced with the carbon capture and storage (CCS) systems, which are used for the reduction of CO_2 from the flue gas of the fossil fired power plants in order to reduce the global warming. The removed CO_2 can be used for other technology such as extraction of oil or stored. CCS consists of three separate technologies (capture, transport and storage). While CCS technology for reduction of CO_2 from exhaust gas is quite promising there are several drawbacks. Very important are issues related to effect of impurities in the removed CO2 gas. A similar issue is researched for the pinch point shift within the S-CO_2 cycle heat exchangers. In this case the captured CO_2 is a multiple-component mixture by definition. This paper is focused on the research of CO_2 mixtures and their effect on heat exchangers in the S-CO_2 cycles and the CCS systems. Some other effects on compressor are mentioned as well. The effect of typical impurities in the S-CO2 cycles (N_2, He, O_2, and Ar) and from the CCS technology (H_2, H_2S, CH_4 and CO) on the heat exchanger size and pressure drop are investigated. It is shown that in most cases mixtures cause an increase of the heat exchanger volume and the increase of the pressure drop. The synergistic research on CO_2 mixtures is important for both technologies. This synergy will bring new interesting findings that will help development of both the CSS system and the S-CO_2 cycles.

INTRODUCTION

The supercritical carbon dioxide (S-CO_2) cycles are recently very perspective and are researched all around the world. They have many applications in many technologies ranging from nuclear energy through geothermal, solar and waste heat recovery systems. Nevertheless, this cycle has several issues. Probably the most important and well known is the existence of the pinch point in heat exchangers, which significantly affects their design. The pinch point is caused by the variations of heat capacity of CO_2 and occurs when the heat capacity of the hot and cold streams (each at a different pressure level) intersect. Due to the pinch point, the heat exchangers may have a large size and low efficiency. However, this point can be removed in several ways. One of them is the addition of small amount of other substance into the pure CO_2. [1]

Furthermore, as it is difficult to use a 100 % pure CO_2 in the S-CO_2 cycles so one may expect about 1% of mole fraction of other substances in it. These impurities are present in working medium and the resulting mixture of CO_2 may lead to the disappearance of the pinch point in the regenerative heat exchanger, on the other hand the impurities have a negative effect on other components such as compressor or cooler [2].

The CCS systems are very perspective for the reduction of CO_2 from the flue gas of the fossil fired power plants. However, the captured CO_2 is a multiple-component mixture with the same negative effect on the CCS system components as in the S-CO_2 cycles. This effect is especially high for the transport and the storage part of the CCS system.

In the CCS systems CO_2 is used in the supercritical state or close to the critical pressure as well as in the case of the S-CO_2 cycles. The reason is the better transport properties of CO_2 mainly the high density. The transport parameters depend on the phase of CO_2 [3]. It can be done in the gas phase or in the liquid phase. For the gas phase the transport pressure is about 15 MPa (depending on the storage, the transport line and the utilization). The liquid phase has a typical transport pressure of about 6.5 MPa. [3]

A compressor station is used to achieve the required transport pressure. Coolers cool down CO_2 to the required transport temperature which can be below 0°C (liquid phase). Hence problems with mixtures in the S-CO_2 cycles are quite the same as for the transport of CO_2. A full understanding of the effect of mixtures on heat exchangers and compressors is necessary.

A very interesting possibility is to use CO_2 from storage as a working medium in the S-CO_2 cycles or in other systems which use CO_2 as a working medium. However, mixtures from capture will probably have a negative effect on the cycle efficiency. Operating costs will be decreased if transport of pure CO_2 is problematic and CCS system is operated near the cycle. Mixture from CCS will reduce operating cost. Other way is the implementation of the S-CO_2 cycles in the compressor stations or other parts of the CCS systems as cycles for waste heat recovery.

This paper is focused on the research of CO_2 mixtures and their effect on heat exchangers in the S-CO_2 cycles and the CCS systems.

THE DESCRIPTION OF THE S-CO_2 CYCLE

The S-CO_2 cycle is a gas cycle developed from the Ericsson-Brayton cycle, which offers many different layouts. The basic layouts are. [4].

- Simple Brayton cycle
- Re-compression cycle
- Pre-compression cycle
- Split expansion cycle
- Partial cooling cycle

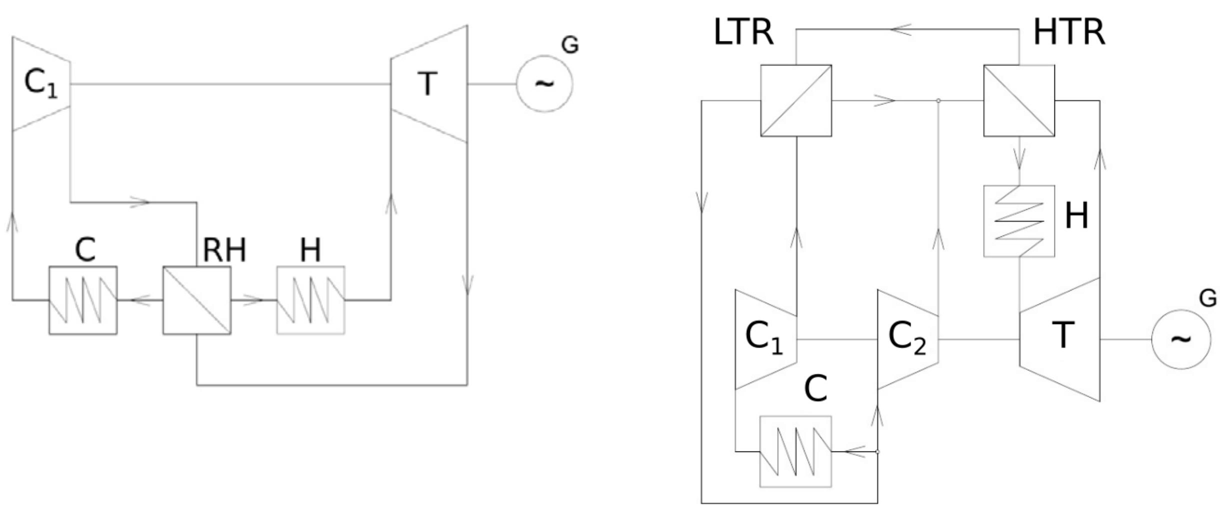

Figure 1.: Simple Brayton cycle (a) and recompression cycle (b) layout

These cycles were described already in the second half of the 20th century [5]. There are many other layouts of these cycles for solar, geothermal power plant and waste heat recovery. The main advantages of the S-CO_2 cycles are that they are simpler and more compact compared to the Rankine-Clausius cycle. Hence, the S-CO_2 cycles are likely to have lower costs, shorter construction period and shorter commissioning period. These benefits come from the properties of CO_2. On the other hand, properties of CO_2 have a negative effect on some components and they affect the behavior of the cycle and the cycle efficiency.

The simple Brayton cycle and the recompression cycle are shown in Figure 1. These cycles have a turbine (T), one or two compressors (C1 and C2), recuperative heat exchanger(s) (RH or LTR and HTR), a cooler (C) and a heater (H).

THE DESCRIPTION OF THE CCS TECHOLOGY

The CCS technologies are used to capture CO_2 from flue gas of the fossil fired power stations, transport it and store it on a selected place. The system first captures CO_2 from flue gas. The capture can be done by three basic methods: the pre-combustion method, the post-combustion method and the oxy-fuel combustion.

The capture of CO_2 in the pre-combustion method is done before the combustion and it is a part of fuel gasification. The capture in the post combustion method is simple for construction, because capture is done after combustion. Thus, this capture system can be built at the existing fossil power plants. In the oxy-fuel combustion the fuel is combusted with pure O_2 and with subsequently CO_2 captured. Capture of CO_2 can be done for cement, concrete, iron and steel industry as well. [3]

Other part of the CCS technology is the transport of CO_2. In this part CO_2 is transported to the specific place, where it is prepared for storage or for injection to the oil fields. The transport is selected according to the place of storage or according to the future use and based on the amount of CO_2 which is captured. Currently, the transport can be done in liquid or gaseous phase. The transport of the gaseous phase is done through pipeline. The pipeline can be used for both type of storage. The transport of liquid phase is done through tanks for CO_2 or by ship, train or truck according to the type of the storage method. The transport parameters of CO_2 are different for the gaseous phase and for the liquid phase. A compression station is used for the pipeline transport for the transport by tanks. Pipelines operates from 8.6 to 20 MPa with the ambient temperature from 4 °C to 38° C [3]. Booster stations must be used for the pipeline transport because of the pressure drop along the pipeline. The number of the booster stations depends on the length of the pipeline. The compression station for a pipeline is shown in Figure 2.

The transport pressure for liquid CO_2 is in the range from 0.52 MPa up to 7.3 MPa [3]. The most common parameters are pressure of 0.65 MPa and the temperature of about -50 °C [6]. A compression station for the transportation of liquid phase of CO_2 is shown in Figure 3. The storage can be done onshore or offshore. The transport for an onshore storage can be done with a pipeline or tanks. It is the same as for liquid. Type of transport depends on the distance between the capture and the storage sites.

The mixtures of CO_2 from capture differ based on the separation method of CO_2 and the type of industry on which the CCS system is employed. The basic components of mixture from capture are N_2, O_2, CO, Ar, H_2S, H_2 and H_2O. An example of mixture of CO_2 for transport in pipelines is shown in Table 1.

Table 1. CO_2 quality recommendation for pipeline transport [1].

Component	H_2O	H_2S	CO	CH_4	N_2	O_2	Ar	H_2	CO_2
	Ppm	Ppm	Ppm	vol.%*	vol.%*	vol.%*	vol.%*	vol.%*	%
Concentration	500	200	2000	< 4	< 4	-	< 4	< 4	>95.5%
*all non-condensable gases									

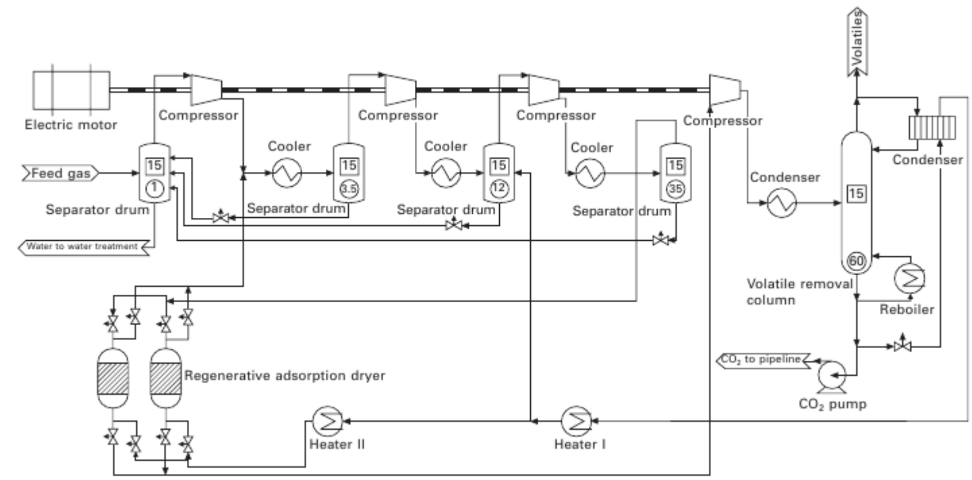

Figure 2.: Compression station for pipeline [3].

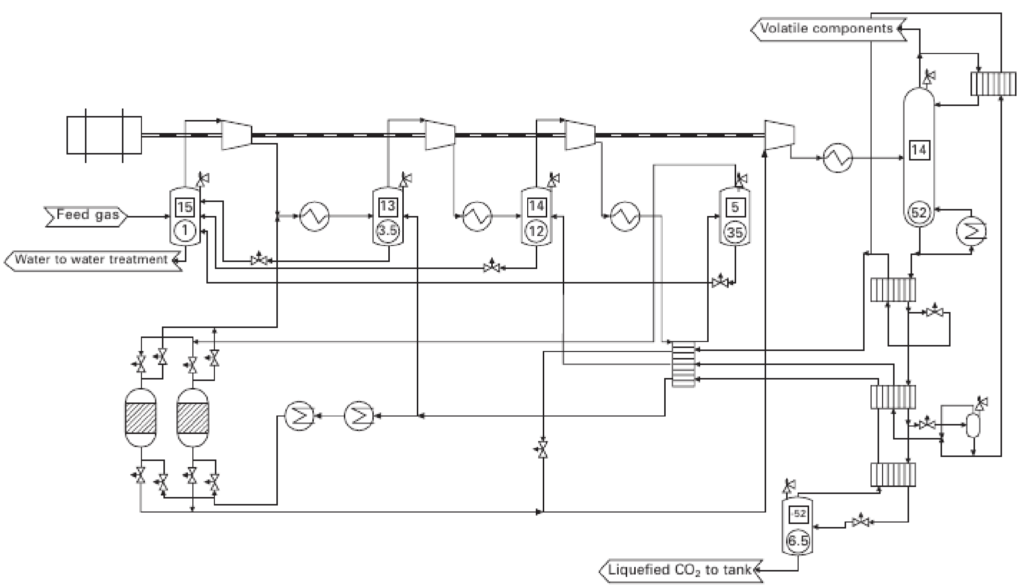

Figure 3.: Compression station for transport of liquid phase of CO_2 [3]

THE DESCRIPTION OF CO_2 PROPERTIES

Carbon dioxide is a triatomic molecule. CO_2 is gas at ambient conditions. The temperature of sublimation is -78.51 °C, the melting point temperature is -56.6 °C for pressure 518 kPa. The critical temperature is 30.98 °C and the critical pressure is 7.38 MPa. The critical density is 464 kg/m^3. In the area near the critical point abrupt changes of density even for small temperature change occur. At the critical point the density of the gaseous and the liquid phase are equal.

These property changes affect the behavior of each component of systems with S-CO_2. The effect can be both negative or positive. In the case of compression near critical point the property changes have a positive effect on the compression (i.e. the reduction of the compressor work). The negative effect appears in a heat exchanger. According to pressures in the heat exchanger the pinch point may occur. The pinch point means the minimum temperature gradient in a heat exchanger. This problem is especially pronounced for heat exchangers with S-CO_2 on hot and cold side close to the critical temperature. For the recuperative heat exchanger, the zero temperature gradient may appear and the transfer of heat is stopped. This problem is caused by the variations of heat capacity of CO_2. Previous research shows that from the known heat capacity for hot and cold side. The location of the pinch point can be defined [1]. Figure 4 shows the temperature of the pinch point according to the pressure of hot and cold side of the heat exchanger. The pinch point can be removed with gaseous minor constituents which are injected in to the pure CO_2. However, this will introduce a negative effect on other components, they mainly the compressor work will increase.

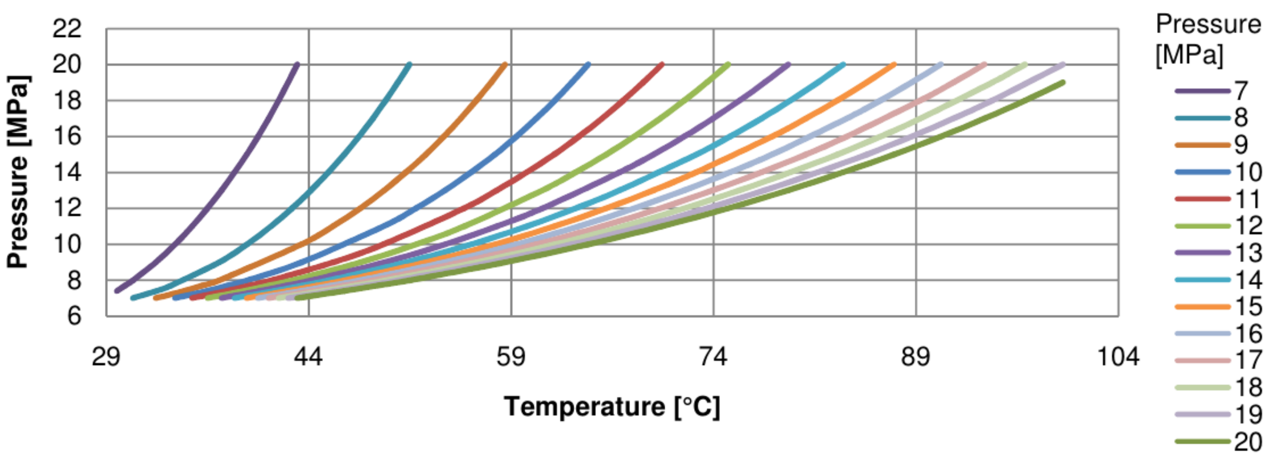

Figure 4.: Dependence of the pinch point location on the temperature and pressure [1]

CO_2 FROM THE CCS TECHNOLOGIES

CO_2 from CCS technology has a different quality of mixture according to the capture process and the system where the capture is done. The mixtures are different and depend on capture technology. Table 2 shows the mixtures for the pre-combustion, the post-combustion and the oxy-fuel combustion. CO_2 from capture is a multiple-component mixture with the same negative effect on components in the CCS systems as in the S-CO_2 cycle. These effects are important mainly for the transport and the storage. So the above mentioned problems with mixtures in S-CO_2 cycles are quite the same for the transport of CO_2 in the CCS systems. A full understanding of the effects of mixtures on heat exchangers and compressors is thus necessary.

It was shown that the CCS systems and the S-CO_2 cycles have the same issues. The possibility to use CO_2 from capture as a working medium in the S-CO_2 cycles or in other systems which use CO_2 as a working medium is very interesting. However, the mixtures will probably have a negative effect on the cycle efficiency, even if the cycle will be operated near the transport line or the capture and storage site. The S-CO_2 cycles can be implemented in compression stations or in other parts of the CCS systems as a cycle for waste heat recovery [7]. The mixtures from the CCS systems thus might decrease the cost of the cycle.

According to the Table 2 it is obvious that the fraction of CO_2 is more than 95 % and the concentration of impurities is less than 5 %. From previous research it is known that the effect of mixtures on a heat exchanger is quite small for 1 % of mole fraction of other substance [2]. Table 3 shows this effect for a cooler. Results from Table 3 are for the shell and tube heat exchanger.

The gaseous mixtures have an effect on the design, the heat transfer and the pressure drops. Figure 5 shows the effect of mixtures on the pressure drops for different binary mixtures. The primary medium is CO_2 and mixtures of CO_2; the cooling medium is water. The parameters for the calculation are shown in Table 4.

The heat exchanger is a single pass shell and tube heat exchanger in the counter current flow arrangement. The outer casing consists of a high pressure casing with the dimensions of 120 x 10 mm. Inside the high pressure tube there is a set of 37 tubes, each with the dimensions of 10 x 1.5 mm.

Table 2. Mixtures of CO2 for different capture technology [8].

Table 3. Total length of cooler for mole fraction 0.01 and 0.05. [2]

Mole fraction	0.01	0.05	[-]
Pure CO_2	2.33		[m]
CO_2 with He	2.60	4.91	
CO_2 with Ar	2.44	3.17	
CO_2 with CO	2.52	3.65	
CO_2 with O_2	2.49	3.49	
CO_2 with N_2	2.51	3.45	

Table 4. Main parameters of the cooler.

Mass flow of side with CO_2	2.5	[kg/s]
Mass flow of side with H_2O	2	[kg/s]
Inlet temperature of side with CO_2	60	[°C]
Outlet temperature of side with CO_2	32	[°C]
Inlet temperature of side with H_2O	25	[°C]
Pressure of side with CO_2	12	[MPa]
Pressure of side with H_2O	1.5	[MPa]

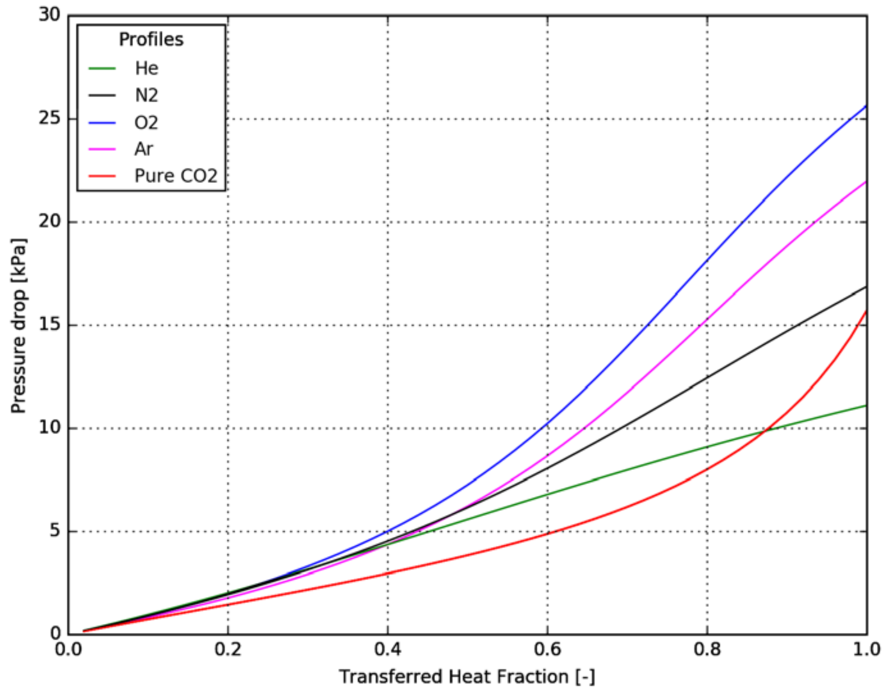

Figure 5.: Pressure drops for mixtures of CO_2 (CO_2 with He, N_2, O_2, Ar)

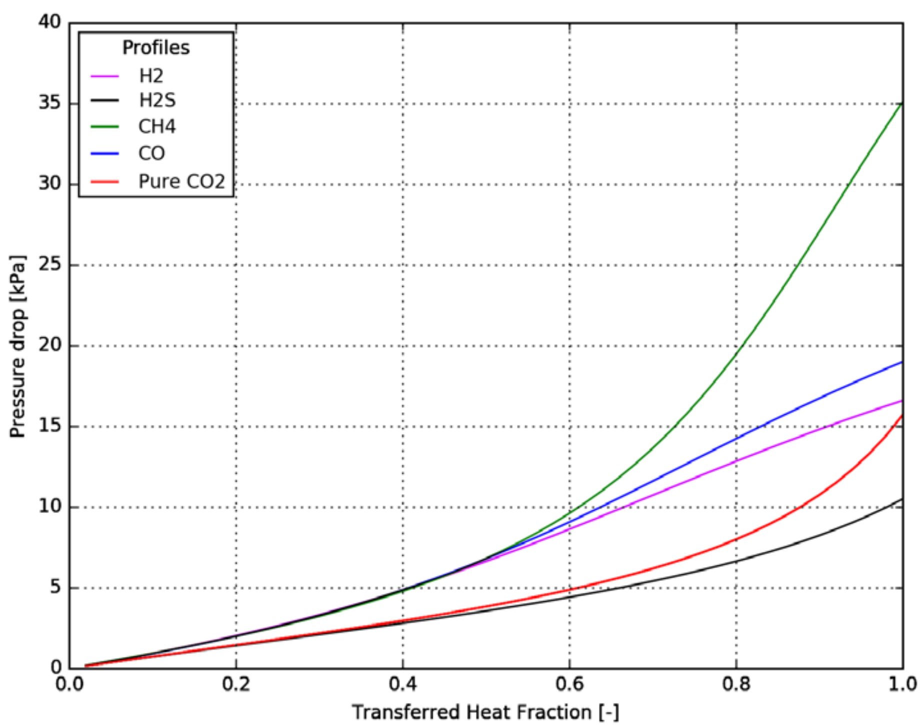

Figure 6.: Pressure drops for mixture of CO_2 (CO_2 with H_2, H_2S, CH_4, CO)

The used gases are N_2, He, O_2, and Ar. These gases are the typical impurities in the S-CO_2 cycle. They have a positive effect on the shift of the pinch point. On the other hand, they have a negative effect on the heat transfer and the total length. According to the Table 3 this effect is significant. According to the Figure 5 it is obvious that the used mixtures increase the pressure drop except for helium.

The similar results can be seen for other mixtures. Figure 6 shows the pressure drops for other binary mixtures with H_2, H_2S, CH_4 and CO. These are the typical components of mixture of CO_2 from the capture technology. Figure 6 shows similar result as Figure 5. It can be seen that all mixtures except the mixture of CO_2 - H_2S increase the pressure drop.

Multicomponent mixtures will likely have a similar effect as the binary mixtures. However, the trend will be probably different. Research of multicomponent mixture is necessary for both CCS systems and the S-CO_2 cycles and will be done in the future.

SUMMARY AND CONCLUSIONS

It was shown that the CCS systems and the S-CO_2 cycles suffer from the same issues when impurities are mixed with the pure CO_2. These impurities are always present in the captured CO_2 and to some extent are present in the S-CO_2 cycles as well. The mole fraction of mixtures depends on the separation system and on the source of CO_2.

The CCS technology, especially its transport part, consists of similar components (heat exchangers and compressors) as the S-CO_2 cycles. Although the design of compressors for the CCS system transport part is slightly different than that for the S-CO_2 cycles, the effect of mixtures on compression is similar. Shift of critical point is possible, but with a negative effect on the compression near the critical point.

The mixtures can be used to remove the pinch point, but in most cases their use leads to the reduced heat transfer, which results in larger heat exchangers with higher pressure drop. So far only the binary mixtures were researched, but similar behavior is expected for the multicomponent mixtures. This research will be done in the future.

Research of the effect of mixtures on the heat exchangers and compressors is one type of the S-CO_2 cycle and the CCS system synergy. Mixtures in the CCS technology and the S-CO_2 cycles are primarily considered as impurities. However, same gases can be injected into the pure CO_2 on purpose in order to shift the pinch point. Other type of synergy is the use of CO_2 as a working medium in the S-CO_2 cycles in the compressor stations or other part of the CCS system as a cycle for waste heat recovery. Implementation of the S-CO_2 cycles to the CCS systems is very interesting and has a good perspective for the future systems. CO_2 from capture can be used as a working medium, thus reducing issues with CO_2 storage and transport. Therefore, the synergistic research on CO_2 mixtures is important. Synergy of research for both technologies, the CCS system and the S-CO_2 cycles, will bring new interesting findings that will help development of both the CSS system and the S-CO_2 cycles.

NOMENCLATURE

CO_2	=	Carbon dioxide
Ar	=	Argon
He	=	Helium
N_2	=	Nitrogen
O_2	=	Oxygen
CCS	=	Carbon capture and storage
CO	=	Carbon monoxide

H_2 = Hydrogen
H_2S = Hydrogen Sulfide
CH_4 = Methane

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