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Influence of refrigerants on a small-scale liquefied natural gas production process

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ABSTRACT: *An optimized, small-scale liquefied natural gas production process based on nitrogen refrigerant has been recently proposed by Khan et al (Khan et al. (2015). Knowledge inspired investigation of selected parameters on energy consumption in nitrogen single and dual expander processes of natural gas liquefaction, Journal of Natural Gas Science and Engineering,* ***23****, 324-337). In the above cited work, both single and dual expander processes were analyzed and findings suggest that the specific energy requirement for the dual expander process reduced by 33 percent. In this paper, we propose an even more optimized process following a study of the influence of three single refrigerants (nitrogen, methane and argon) and one mixed refrigerant (argon-methane mixture) on energy savings and LNG productivity. The dual expander process flowsheet originally proposed by Khan et al. and apropprietary process simulation software are used for the present study. A comparison of our process with the optimized process earlier proposed by Khan et al (2015) shows significant reduction in energy consumption, with the specific energy requirement further decreasing by over 50 percent.*

KEYWORDS: *LNG, Natural Gas Liquefaction, Energy Efficiency Enhancement, Unit Power Consunmption*

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I. INTRODUCTION

There has been a lot of interest in the expander natural gas liquefaction process; both for onshore and offshore fields (Khan et al., 2015; Khan and Lee, 2013). Advances have been made from the single expander liquefaction process to the dual expander liquefaction process (Khan et al., 2015). Specifically, Khan and co-workers (Khan et al. 2015) proposed a nitrogen-based single expander process and their further introduction of the dual expander process was to achieve lower specific energy consumption (Khan et al., 2015). The present work focuses on the use of different pure refrigerants and a mixture of refrigerants for natural gas refrigeration and liquefaction in order to demonstrate which of the different refrigerant options would lead to a more efficient liquefied natural gas (LNG) production. Figures 1 and 2 from Khan et al (2015) show the basic flowsheets of the single expander and dual expander processes, respectively (Khan et al. 2015), where they demonstrated that the use of the dual expander process has significant advantages over the single expander process.

II. PROCESS MODELLING AND ANALYSIS

This work involves the use of the latest version of a proprietary, steady-state simulation software (AspenTech, 2016; Unisim, 2006) for the modelling and analysis of the dual expander LNG production process. We use the popular Peng-Robinson equation of state to calculate the thermodynamic states of the process streams (Khan et al., 2015). The feed conditions and compositions of the simulations were adapted from Khan et al. (2015). Figures 1 and 2 illustrate process flow schemes used in the study while Table 1 lists some of the modelling assumptions.

The single expander cycle (see Figure 1) uses only one loop for the liquefaction of natural gas where all streams (from 1-13) are shown. The natural gas feed enters the LNG exchanger at a compressed state of 50 bar. The pressurized natural gas feed after being sub-cooled exits the LNG exchanger (LNG-100) in liquefied form at -149 0C. The sub-cooled natural gas is then expanded to atmospheric pressure of 1.2 bar before going to the storage tank where approximately 8% vapor (boil-off-gas) are formed at -158.5 0C. In the refrigerant cycle (shown with blue color in Figure 1), the high pressure nitrogen refrigerant (100 bar) enters the LNG exchanger and is self-refrigerated from ambient temperature of 30 0C to -38.08 0C. The nitrogen gas is then expanded to 7 bar in an expander.

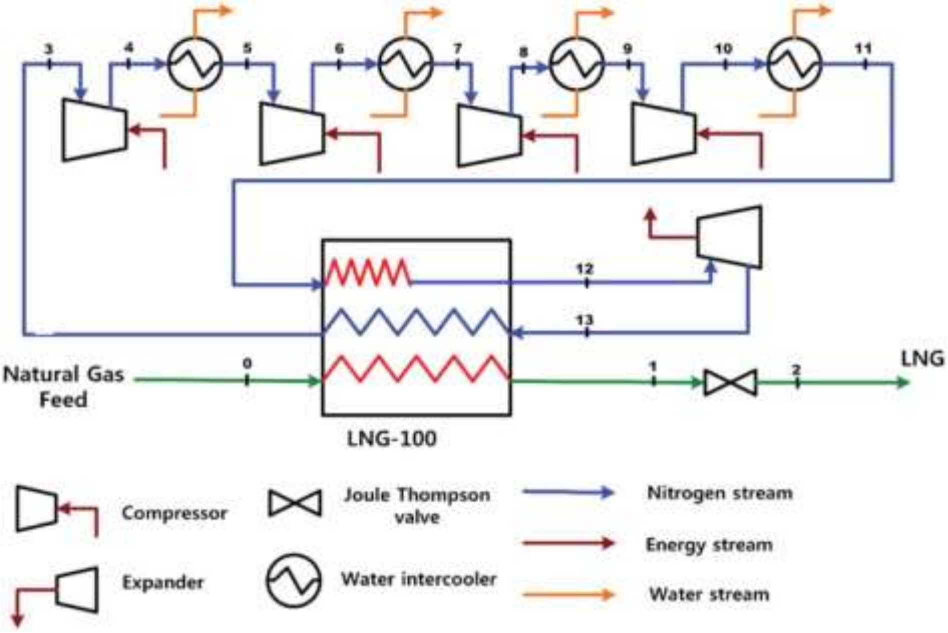


Fig.1. A schematic of a single expander natural gas liquefaction process (Adapted from Khan et al, 2015)

This expansion reduces the temperature of the already cooled gas to -153 0C. The cold nitrogen gas re-enters the liquefaction box providing refrigeration and exits in the warm state at 27 0C (Khan et al. 2015). The warm gas is taken to the compressor cooler assembly, where the nitrogen is recompressed in a staged compression with intermediate cooling, to be expanded again. The energy obtained from the expander is used to partially recompress the nitrogen (Khan et al. 2015). The system requires a small nitrogen generation unit to provide the nitrogen needed to maintain the losses through the compressor seals (Khan et al., 2015). The distinctive shortcoming of single N2 expander process is that the entire refrigerant is expanded to the lowest temperature, even though most is required at a higher temperature (Khan et al. 2015). This introduces significant irreversibility to heat exchanger because of the large temperature difference and causes the high compression energy requirement. To overcome the large associated irreversibility and to achieve a low temperature with less compression work and to circumvent the heat exchanger constraints, the dual expander process is introduced which is essentially an addition of another expander, the so-called dual-expander natural gas liquefaction process (Khan et al. 2015).

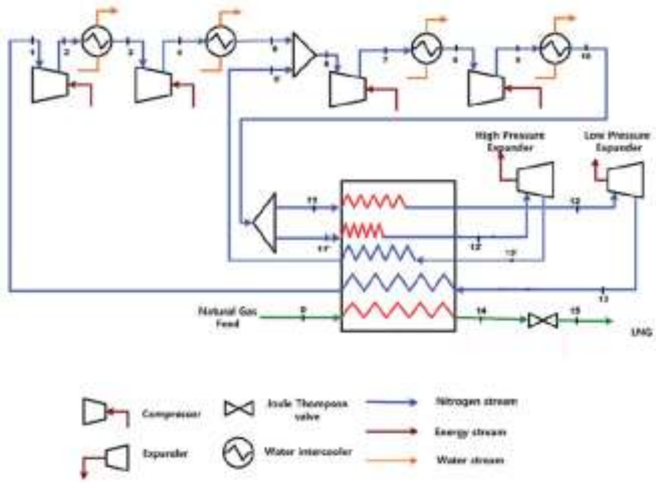


Fig. 2. A schematic of a dual expander natural gas liquefaction process (Adapted from Khan et al, 2015).

Through this dual expander process, the natural gas feed with same composition as the single expander enters the cryogenic facility under high pressure (50 bar, 30 ^{0}C) and after exchanging sensible heat with the refrigerant, the natural gas feed leaves the heat exchanger at -149 ^{0}C, and is flashed to atmospheric pressure and finally sent to the storage facility at -158 ^{0}C (Khan et al. 2015). The nitrogen flows into two different cycles at two different temperature levels. The first cycle with a small pressure drop (99 bar / 31 bar) and with a large nitrogen flow rate (approximately 80%) is used for the pre-cooling (at -85 ^{0}C) of natural gas, whereas the second cycle with a low refrigerant flow rate (remaining 20%) operating with a high pressure drop (99 bar/15 bar) at -153 ^{0}C is used for sub-cooling (Khan et al. 2015). The splitting of nitrogen at two different pressure levels incurs a small capital cost in terms of the extra expander but the energy savings due to near reversible operation can justify the additional expander capital cost (Khan et al. 2015). In section 3, we present simulation results that would help us ascertain how the use of other refrigerants other that nitrogen can either reduce or increase the efficiency and productivity of the dual expansion natural gas liquefaction process described above and based on Figure 2.

Table 1: Simulation condition and assumptions

Property	Condition
Natural Gas Temperature	30 oC
Natural Gas Pressure	50 bar
Natural Gas Flowr Rate	1.0 kg/hr
Natural Gas Composition (mole fraction)	(adapted from Khan et al., 2015)
Methane	91.30
Ethane	5.40
Propane	2.10
i-Butane	0.50
n-Butane	0.50
i-Pentane	0.01
n-Pentane	0.01
Nitrogen	0.20

III. SIMULATIONS RESULTS AND DISCUSSION

Here, we introduce two different pure refrigerants other than nitrogen (i.e. argon and methane) as well as a mixture of refrigerants (argon-methane mixture) in order to investigate the thermodynamic performance of the dual expander natural gas liquefaction process. We will simulate the process using the same simulation basis and operating conditions. This methodology would help us determine which of the refrigerant options exhibit the best performance characteristics of the dual expansion process. A sensitivity study of the following parameters are performed and used to evaluate the liquefaction cycle: stage temperature,precooling fluid flow rate,sub-cooling fluid flow rate, sub-cooling fluid discharge pressure, and heat transfer efficiency. The stage temperature is the temperature of the pre-cooled refrigerant stream or inlet stream into the lower pressure expander represented by stream 12 in Figure 2. We increased the stage temperature from -100^{o}C to 5^{o}C taking note of the LNG outlet temperature and the compressor duty of the four compressors used in the cycle. We also decreased the precooling fluid flow rate from 14.4 kg/hr to 0.5 kg/hr and recorded the changes in compressor duty and LNG temperature values. The sub-cooling fluid flow rate, suction pressure, and discharge pressure are varied from 3.0kg/hr to 0,3kg/hr, 50 bar to 10 bar, and 100 bar to 10 bar, respectively, with the corresponding values of LNG temperature and compressor duty computed.

3.1 Effect of Stage Temperature

Figure 3 shows the performance of the dual expander process based on the four refrigerant options, including the base case (i.e. nitrogen). We observe that increasing stage temperature slightly decreases the total compressor duty. This behavior could be attributed to relatively lower pressure ratios of the compressors. Figure 3 also indicates that the use of argon refrigerant provides the best performance of the cycle, with methane exhibiting the least performance among the four options. Figure 4 suggests that increasing the stage temperature will aid both liquefaction and subcooling of the natural gas, with methane refrigerant tending to subcool more than the rest.

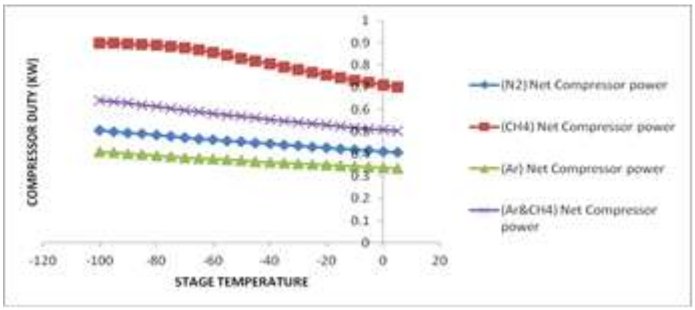


Fig. 3. Compressor duty values as a function of stage temperature for the four refrigerant options.

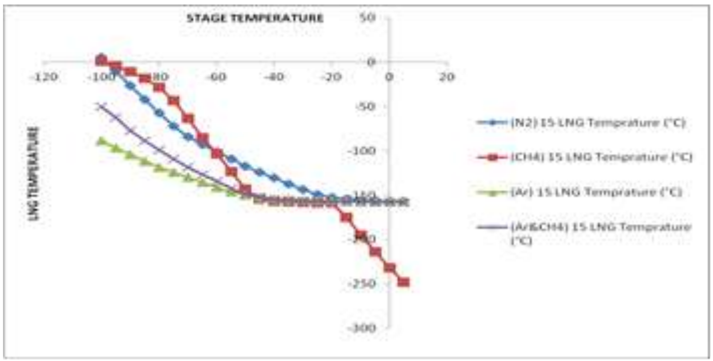


Fig. 4. LNG temperature values as a function of stage temperature for thefour refrigerant options.

3.2 Effect of Precooling Fluid Flow Rate

Prior to the liquefaction and subcooling stages of the LNG production process, the pre-cooling fluid fraction expands and cools the natural gas from its gaseous state to dew point. Figure 5 shows that changes in precooling fluid flow rate would affect compressor power requirement. The higher the flow rate, the higher the compressor duty regardless of the type of refrigerant in use. Higher flow rate implies higher amount of fluid to be compressed, thus more work for the compressors. Argon refrigerant, again, shows the best performance of the four options while the nitrogen refrigerant and the argon-methane mixed refrigerant show almost similar behavior with respect to compressor power requirements. Pure methane refrigerants trail the rest with the least performance. Figure 6 shows the effect of precooling fluid flow rate on the temperature properties of produced LNG. An increase in the flow rate of the precooling fluid increases the refrigerants' liquefaction and subcooling effects. Since natural gas is mostly methane, hence the reason for the seemingly invariant behaviour of the cycle which uses methane as a refrigerant.

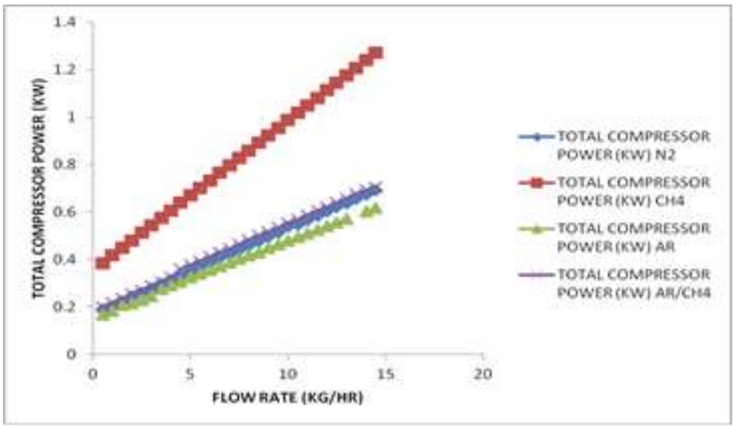


Fig. 5. Precooling fluid flow rate versus total compressor power requirements.

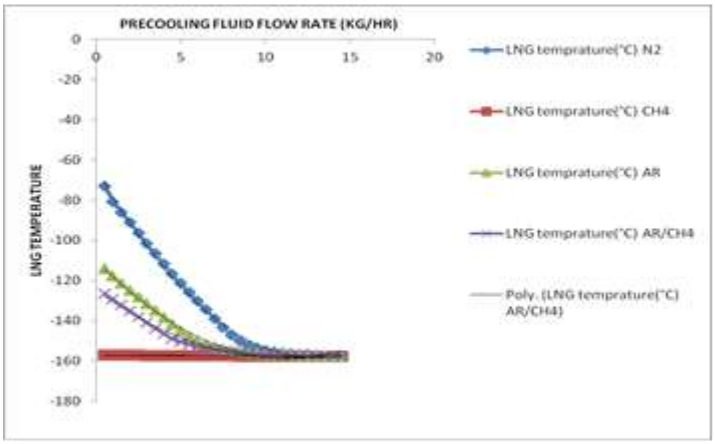


Fig.6. Precooling fluid flow rate versus produced LNG temperature

3.3 Effect of Subcooling Fluid Flow Rate exiting High-Pressure Expander

The sub-cooling fluid flow rate is the rate of the stream returning to the LNG heat exchanger from the high-pressure expander (see Figure 2) which is expected to contribute to the liquefaction of the already precooled natural gas. The compressor duty requirement increases irrespective of the type of refrigerant introduced (see figure 7). The argon refrigerant is again found to provide the best performance, with argon-methane mixture, nitrogen, and methane, respectively following in that order. Figure 8 shows that an increase in the flow rate of the sub-cooling fluid will result in a corresponding drop in the temperature of the produced LNG, with argon refrigerant being the most preferred. This behavior as analyzed above is as expected because argon has a better thermal and flow properties than methane and nitrogen. Hence, at lower flow rate argon tends to absorb more heat than methane and nitrogen which is evidenced in its ability to cool the natural gas more than methane and nitrogen at the same flow rate.

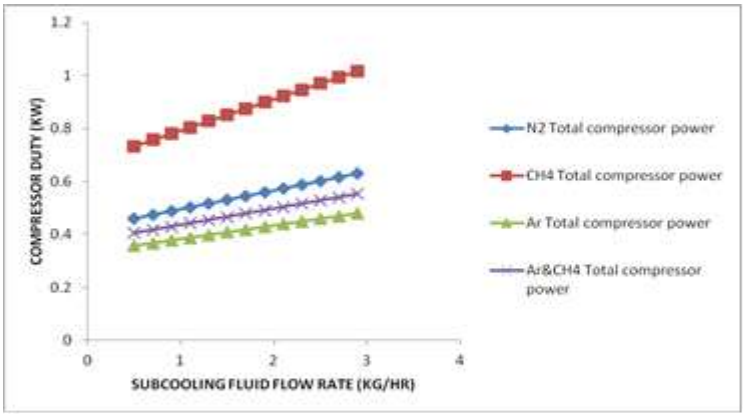


Fig. 7. Sub-cooling fluid flow rate and compressor duty profiles

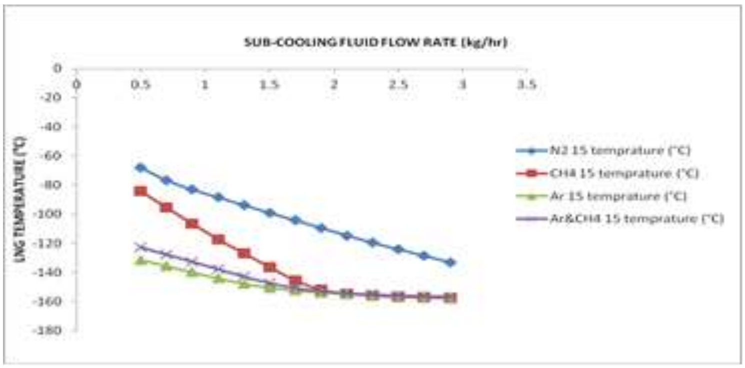


Fig. 8. Sub-cooling fluid flow rate versus produced LNG temperature profiles

3.4 Effect of Sub-cooling Fluid Discharge Pressure

Sub-cooling fluid discharge pressure refers to the pressure at the suction of the first stage compressor (see Figure 2). This pressure is important as it indirectly determines the amount of compression work needed to compliment the energy present in the suction fluid. Figure 9 indicates an increase in the sub-cooling fluid discharge pressure will result in a decrease in the compressor duty requirement. Figures 9 and 10 show that argon is the highest performing refrigerant while methane is the least.

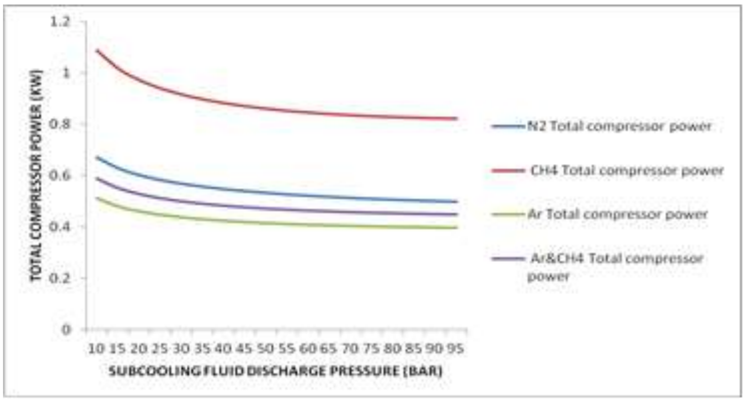


Fig. 9. Sub-cooling fluid discharge pressure versus compressor duty requirement curves.

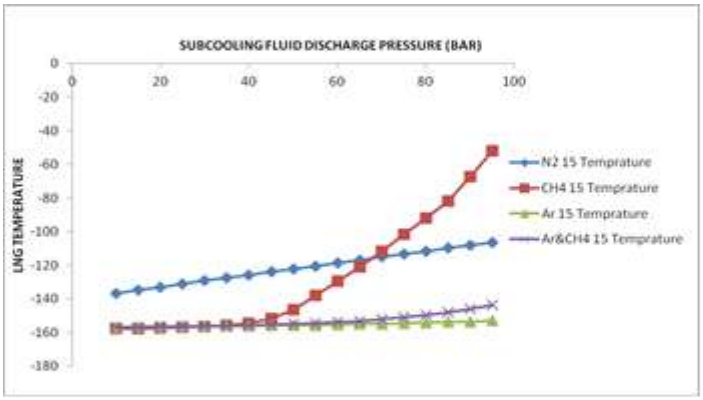
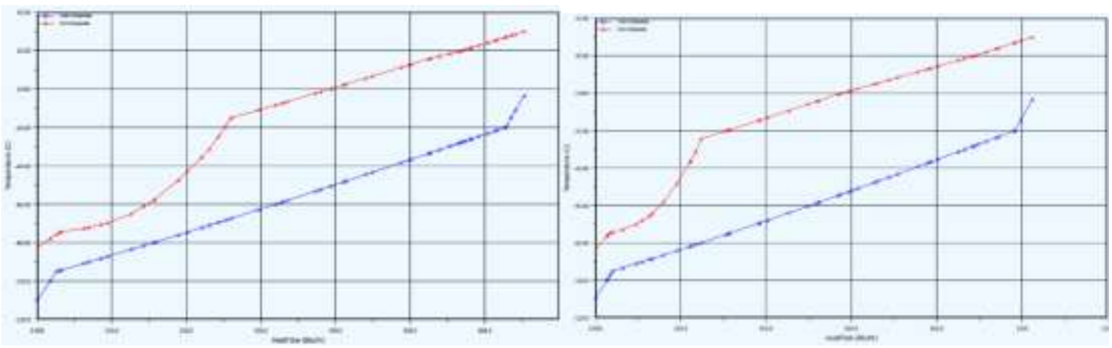


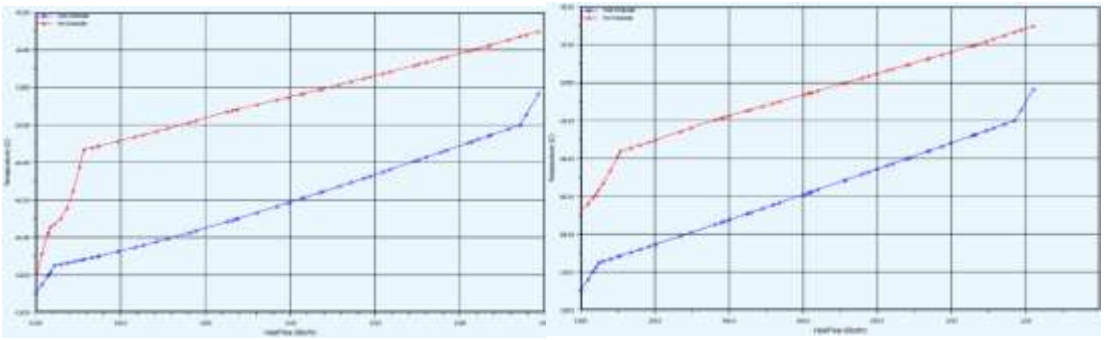
Fig. 10. Sub-cooling fluid discharge pressure versus LNG temperature profiles.

3.5 Heat Transfer Efficiency and Refrigerant Composite Curves

The hot and cold composite curves for pure component argon, argon-methane mixture, pure component methane and pure component nitrogen are illustrated in Figure 11 (a-d).The composite curves for the baseline process (i.e. the nitrogen-based process) shows less efficient heat transfer and more entropy generation in the heat exchanger which makes the process consume more power. Upon adopting the three other refrigerants, the heat exchange process is clearly affected. Overall, we observe the superior performance of the argon-based and argon-methane mixture refrigerants. While the former is mostly attributable to the peculiar properties of argon, the latter can be, in addition, attributed to a mixed refrigerant composition.



(a) pure-component argon **(b) mixture of argon and methane**



(c) pure-component methane **(d) pure-component nitrogen**

Fig. 11. The hot and cold composite curves for: (a) pure component argon, (b) argon-methane mixture, (c) pure component methane and (d) pure component nitrogen.

IV. CONCLUSION

The influence of four different types of refrigerants for a dual expander liquefaction process was investigated with the objective to ascertain which of the refrigerant options would demonstrate the capacity to minimize the energy efficiency and/or specific energy requirements of the LNG production process, with efficiencies much higher than the pure nitrogen-based method proposed by Khan et al (Khan et al., 2015). In particular, replacing nitrogen refrigerant with argon refrigerant could reduce the compression power consumption and increase specific energy requirement of the overall dual expander natural gas liquefaction process by a further 50 percent from the 33 percent initially proposed by Khan et al (Khan et al., 2015).

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