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TECNOLOGIA APPLICATA ALLA REFRIGERAZIONE A TEMPERATURA MOLTO BASSA ED ALLA LIQUEFAZIONE DEL GAS NATURALE

M. STAICOVICI
S.C. VARIA ENERGIA S.R.L.

RESEARCH OF PARTIAL HYBRID COMPRESSION TECHNOLOGY APPLIED TO ULTRA-LOW TEMPERATURE REFRIGERATION AND NATURAL GAS LIQUEFACTION

Staicovici Mihail-Dan
S.C. VARIA ENERGIA S.R.L, M. Eminescu street, nr. 81 B, floor 4, apt. 9, sect. 2, 020 072 Bucuresti, Email: mihail_dan_staicovici@yahoo.com
Tel.: +4 021 210 65 00, +4 0720 26 25 89

Abstract
The Hybrid Compression (HC) new concept, proposed lately for feasible refrigeration and heating, is a synergy of an Absorption Technology Section (ATS) and a Mechanical Vapor Compression Technology Section (MVCTS). According to HC, MVCTS plays the role of sink and heat or just the heat source for ATS, while ATS performs the useful task of cooling or heating, respectively. This work completes HC with a Partial Hybrid Compression (PHC) technology study, proposed to achieve, similar to HC, ultra-low temperature refrigeration (ULTR). PHC uses free low-grade external heat sources to supply the ATS generator, while MVCTS provides the ATS internal sink source, only. Model results of PCH-ULTR are given for single-stage NH_3-H_2O ATS and NH_3 two-stage MVCTS, provided with discharge gas superheating recovery (TWRC). Input data are: a) evaporator temperature, T_{DI}= -75, -70, ..., -45°C; b) external sink source temperature, T_{ss}=9, 18, …, 45°C; c) mixing point temperature, T_M= -25, -20, ..., +5°C. Main output data are: i) PHC cooling effectiveness, COP_{cPHC}; ii) maximum discharge temperature, $T_{CpO,max}$; iii) MVC vs. PHC comparative compressed refrigerant volume, R_V; iv) generator temperature, T_{Mh}, MVCTS and ATS cooling effectiveness, and PHC exergy efficiency. The (i)-(iii) output data show outstanding improvement as compared to HC technology and so much more to MVC, which increases PHC feasibility in ULTR correspondingly. After a former study, of air liquefaction, in last work section HC-and PHC-ULTR are applied again to an important cryogenic topic, concerning this time the liquefied natural gas (LNG) production. PHC-ULTR assisted NG liquefaction process, shows also promise in the future of LNG cryogenics.
Keywords: hybrid compression, mechanical vapor compression, absorption, low temperature refrigeration, discharge gas temperature, refrigeration effectiveness, refrigerant compressed volume, liquefied natural gas.

1. Introduction
The Hybrid Compression (HC) concept was introduced lately by the author with the aim of solving in a more feasible and flexible way the ultra-low temperature refrigeration (ULTR) and ultra-high temperature heat pump heating (UHTH) (Staicovici, 2014, 2015a, b, c, 2016a, b). In this work, further research is outlined in HC-ULTR completion. It has as object the Partial-Hybrid Compression Technology (PHC), first proposed in a prior work in connection with the air liquefaction, (Staicovici, 2017). This research extends PHC-ULTR results on a broader range of operating conditions, with emphasis on comparative PHC- vs. HC-ULTR feasibility. In the last work section, the HC-and PHC-ULTR are applied again to an important cryogenic topic, concerning this time the liquefied natural gas (LNG) production. Finally, conclusions are formulated.

2. Further Research Of Partial-Hybrid Compression Technology Applied To Ultra-Low Temperature Refrigeration

A classic mechanical vapor compression (MVC) plant produces both cooling and heating. Similar to MVC, a HC plant needs two external supplying sources, only, a sink and an electrical (mechanical), respectively. However, in case of HC, the MVC is replaced by a synergy of two mature technologies, i.e. MVC and Absorption, materialized each by a separate HC section. These two technologies complement each other, so the MVC Technology Section (MVCTS) plays the role of both sink and heat sources, or just the heat source, for the Absorption Technology Section (ATS), while ATS performs the useful effect of cooling or heating, respectively. The HC differs basically from another Absorption and MVC synergy, called Hybrid Absorption (HA), where MVC boosts the absorption generator for this operates at lower temperatures, only. The HC vs. MVC higher feasibility comes of HC capacity to bring outstanding improvements in ULTR (Staicovici, 2015c, 2016a),

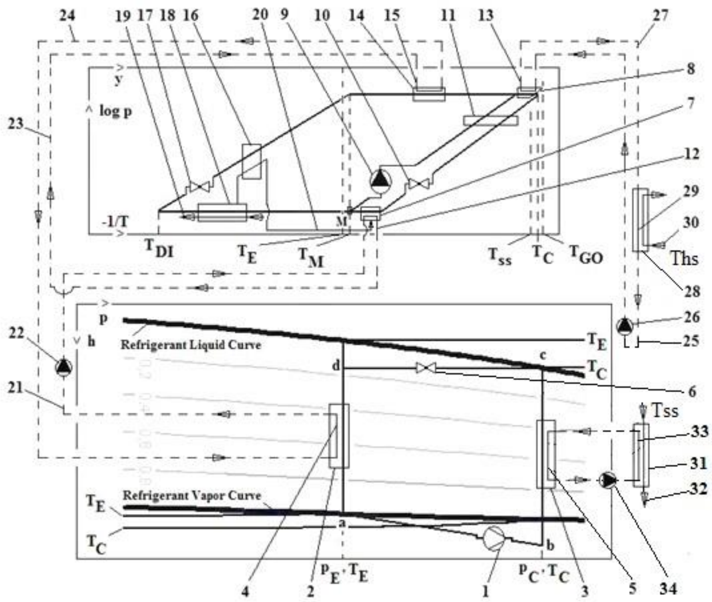


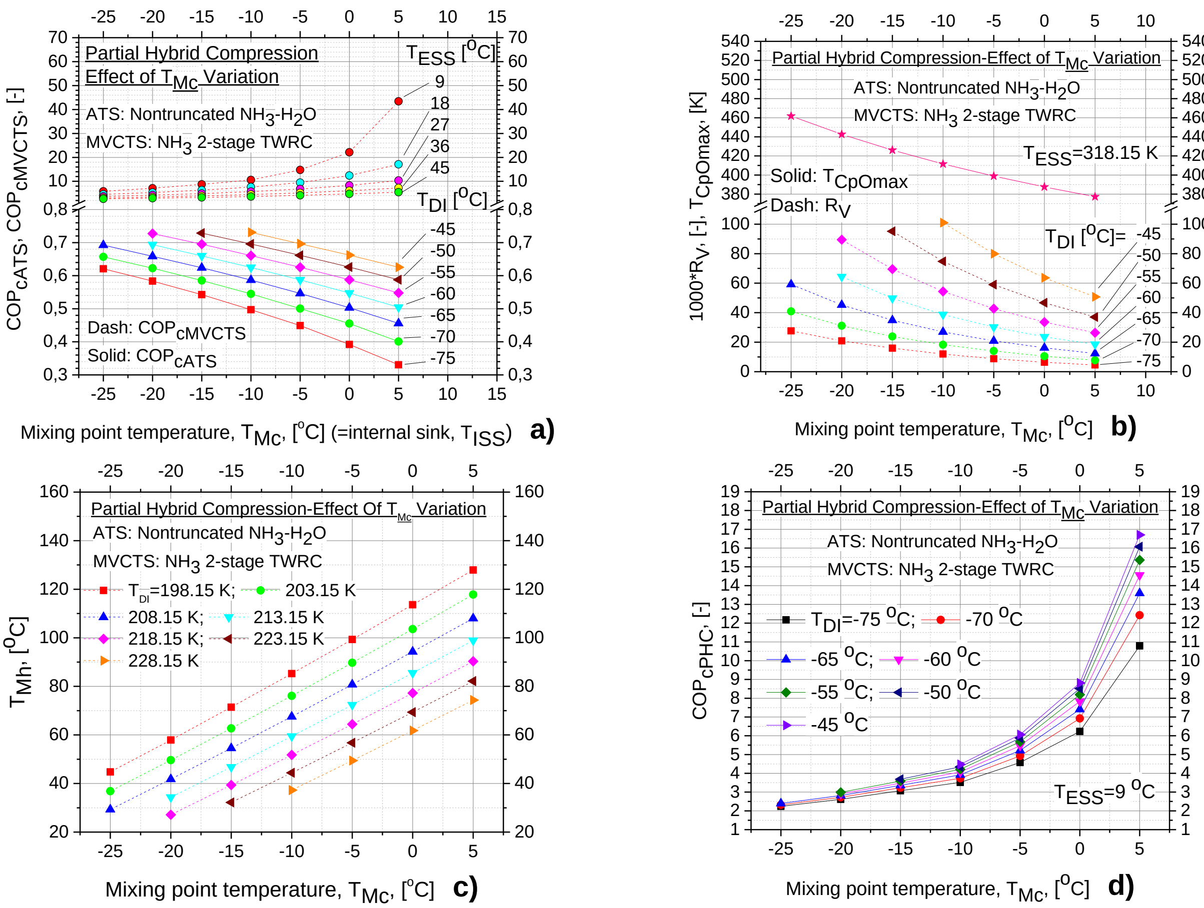
Figure 1. P-h and log p-1/T plot of a PHC cooling cycle provided with the single-stage MVCTS and ATS.

through a: i) much higher comparative cooling effectiveness, COP_{cHC} (up to 50-70 %); ii) compressor operation with discharge temperatures within today accepted values ($T_{CpO,HC} < T_{CpO,max} <180°C$), and iii) much smaller relative compressed refrigerant volume, R_V, up to 6-7times, handled by HC, which is in favor of an important reduction of the compressor physical size. Should the PHC-ULTR be applied, the (i)-(iii) items and feasibility would be further improved. The PHC working bases on the use of low-grade free external heat sources, having temperatures above those of the external sink source, $T_{hs} > T_{Mh} > T_C > T_{ss}$, and supplying the ATS generator. This time, MVCTS reduces its role, comparatively, and becomes an ATS internal sink provider, only, $T_{DI} < T_M$, where the „partial-hybrid" term comes of. The PHC cooling cycle is plotted in Fig. 1 and is described briefly next. The MVCTS and ATS are plotted in the p-h and log p-1/T charts, respectively. The MVCTS evaporator (2), extracts simultaneously the heat rejected by ATS absorber (7) and condenser (14) with the help of an intermediary heat transfer fluid (IHTF), with low freezing point. It covers a closed loop, including the serially connected evaporator coil (4), pipe (21), pump (22), absorber coil

(12), pipe (23), condenser coil (15), pipe (24) and evaporator coil (4). The MVCTS condenser (3) rejects the upgraded heat extracted by the MVCTS evaporator (2) and delivers it to the external sink (32), with the help of IHTF, covering a closed loop including the serially connected condenser coil (5), pump (34), and coil (33), belonging to the sink source heat exchanger (31). The ATS generator-rectifier (8) is supplied by the external heat source (30) with the help of IHTF, covering a closed loop including the serially connected generator-rectifier coil (13), pipe (27), heat source coil (29), receiving heat from heat source (30) in the heat source heat exchanger (28), pipe (25), pump (26) and generator-rectifier coil (13). The PHC, Fig. 1, can have other structures, as well.

3. Pch-Ultr Model Results

Model results of PCH-ULTR are given for NH_3-H_2O single-stage ATS and NH_3 two-stage MVCTS, provided with discharge gas superheating recovery (TWRC, Staicovici, 2014), Figs. 2(a) to 2(h). The input data are: a) evaporator temperature, T_{DI}= -75, -70, -65, -60, -55, -50 and -45°C; b) external sink source temperature, T_{ss} (=T_{ESS}) = 9, 18, 27, 36 and 45 °C; c) mixing point temperature (internal ATS sink), T_{Mc} (=T_{ISS})= -25, -20, -15, -10, -5, 0 and +5°C. The main output data, plotted against the internal mixing point temperature, T_{Mc}, and having T_{DI} as parameter, are the following: i) ATS and MVCTS effectiveness, expressed by COP_{cATS} and COP_{cMVCTS}, respectively, Fig. 2(a); ii) MVC vs. PHC compressor relative compressed volume and maximum discharge gas temperature, R_V and $T_{CpO,max}$, respectively, Fig. 2(b); iii) external free heat source temperature, T_{Mh}, Fig. 2(c). The PHC cooling effectiveness, COP_{cPHC}, Figs. 2(d) to 2(h), has been obtained linking together the items COP_{cMVCTS} and COP_{cATS} of Fig. 2(a), according to, (Staicovici, 2015c):



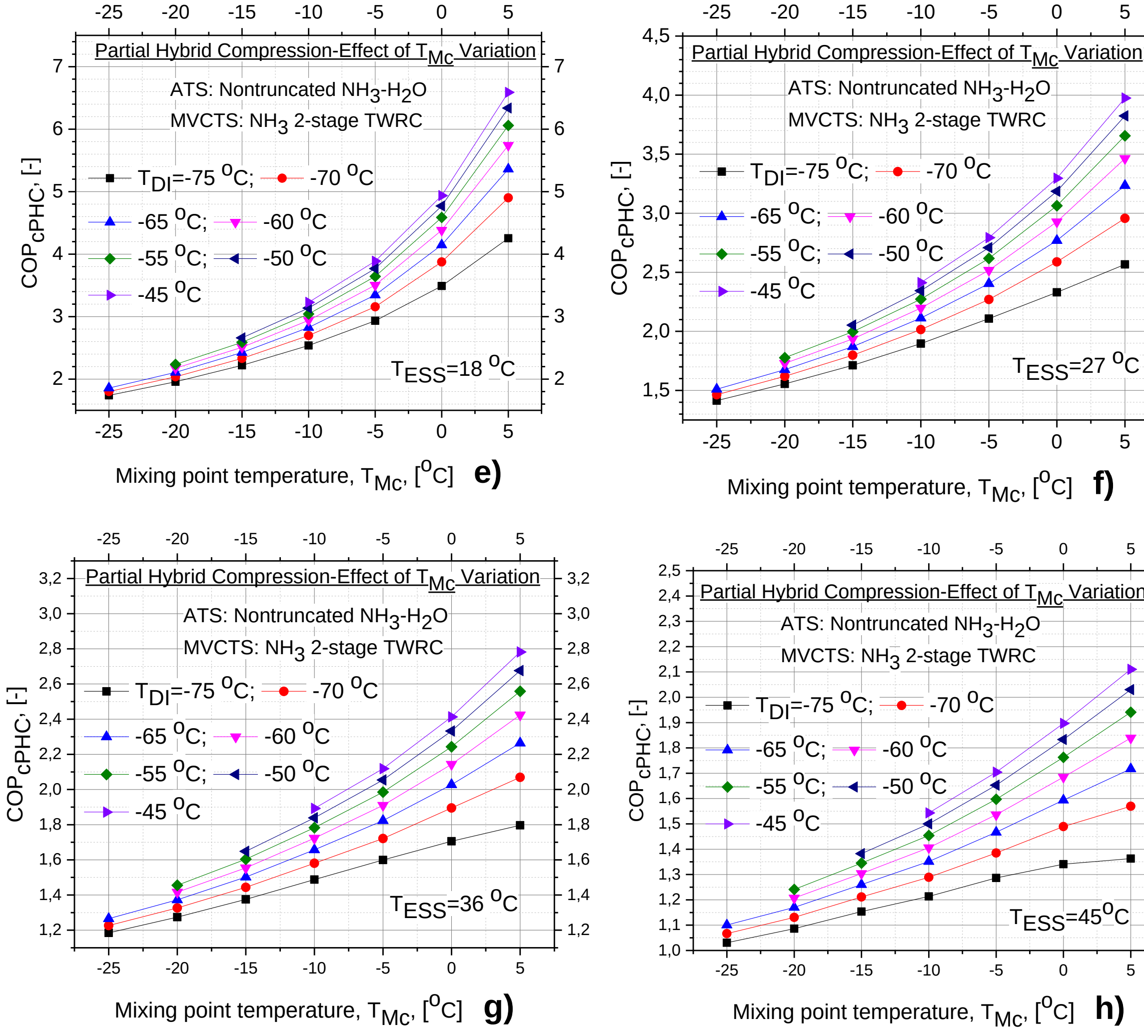
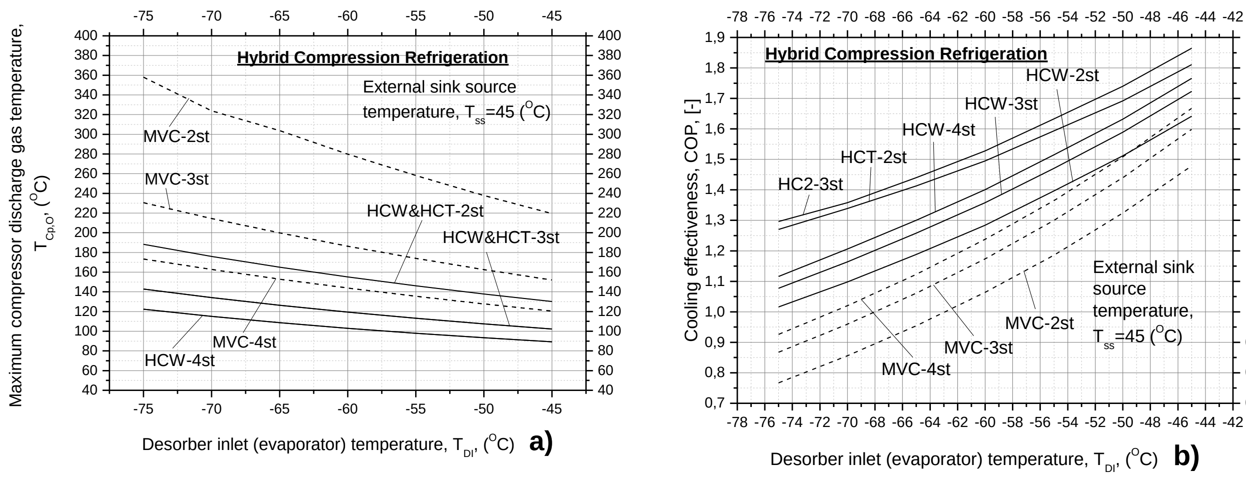


Figure 2. PHC-ULTR model results: a) COP_{cPHC} and COP_{cMVCTS}; b) R_V and $T_{CpO,max}$; c) T_{Mh}; d) to h) COP_{cATS}.



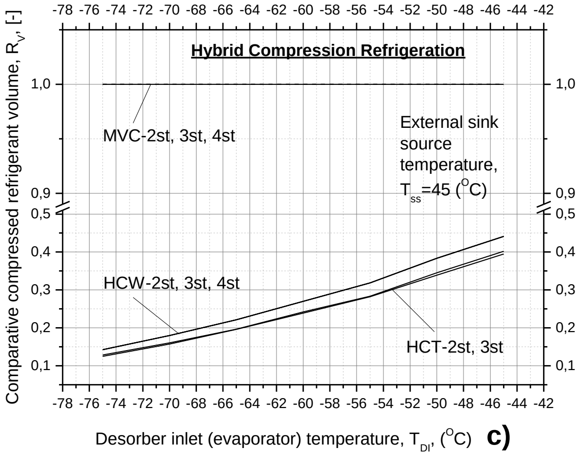


Figure 3. HCW-ULTR, HCT-ULTR and MVC-ULTR results of a) $T_{CpO,max}$, b) COP_c and c) R_v, vs. T_{DI}, helpful in the comparison of PHC-ULTR with HCW- and HCT-ULTR technologies.

$$COP_{cPHC} = \frac{COP_{cMVCTS}}{1+\frac{1}{COP_{cATS}}} \quad (1)$$

Comments of results follow. Indeed, From eqn. (1) it results that COP_{cPHC} increases with T_{Mh} increase. This is explained by the fact that for every T_{DI} the increase of COP_{cMVCTS} with T_{Mh} increase is more important than the decrease of COP_{cATS} with T_{Mh} increase, due to rectification need increase (see COP_{cMVCTS} and COP_{cATS} plot in Fig. 2(a)). However, this remark is true mainly in case of Figs. 2(d) to 2(g), when T_{ESS} < 36 °C. For higher T_{ESS}, (e.g. T_{ESS}=45 °C), T_{Mh} and the rectification need increase significantly, so PHC application becomes critical, especially in case of the lowest values of the ultra-low evaporator temperatures, as Fig. 2(h) shows (see e.g. the plot for T_{DI}=-75 °C). Moreover, the results of PHC-ULTR, obtained with high sink source temperatures, are only slightly better than those of HCW-ULTR and HCT-ULTR, as Fig. 3(b) shows in case of T_{ESS}=45. Continuing results comments, HCW-ULTR and HCT-ULTR, already bring an important COP_{cHC} increase as compared to MVC-ULTR, (Fig. 3(b), Staicovici, 2015c, 2016a). This paper and the former one, (Staicovici, 2017), show that PHC-ULTR is capable to increase further COP_{cPHC} as compared to HCW-ULTR and HCT-ULTR, by cca. 50 to 100 % and more, when the external low-grade heat source temperature covers the range T_{ESS} to T_{ESS} + (50-70)°C. Secondly, the maximum discharge temperature, $T_{CpO,max,}$ decreases continuously with T_{Mc} increase, as a normal behavior. This decrease is higher than that of HCW-ULTR and HCT-ULTR, and so much more than that of MVC-ULTR, Fig. 3(a). A comparison of Fig. 2(b) with Fig. 3(a) for T_{ESS}=45 °C is helpful in this respect. Thirdly, HCW-ULTR and HCT-ULTR benefit of a drastic reduction of the compressed refrigerant volume as compared to MVC-ULTR, expressed by the ratio R_V, Fig. 3(c), (Staicovici, 2015c). PHC-ULTR improves this figure of merit, as compared to HCW-ULTR and HCT-ULTR, in a continuous way with T_{Mc} increase, as Fig. 2(b) shows in case of T_{ESS}=45 °C when compared to the plot of Fig. 3(c) (see also Staicovici, 2017). Concluding, PHC-ULTR shows great improvement of its main parameters comparatively, which is in favor of an increased feasibility of this technology in the future.

4. Research Of Partial Hybrid Compression Technology Applied To Natural Gas Liquefaction

The liquefaction of gases, and particularly of natural gas (NG), is an important, mature industrial technology, (Stamatescu et al., 1982). The permanent increase of the liquid natural gas (LNG) production effectiveness is mandatory. Indeed, the LNG is just an intermediary product transported between NG extraction and delivery to an end-user, so, the lower the energy consumption for its production, the higher the global available energy of NG, and the smaller its environmental impact. One of the methods to achieve this goal implies the use of the expansion process with pre-cooling of the compressed gas. The pre-cooling can be done for example with liquid nitrogen, resulted from the air separation process. In this case, the LNG train is located at the place of the air separation unit (ASU). However, in this case, the ASU-LNG-coupling might not be very cost-effective, as the ASU is expensive and not always necessary. Another option for pre-cooling implies the use of MVC cooling units (up to -50 °C), running with propane or ammonia, but theirs effectiveness is quite reduced. In order to avoid the drawbacks mentioned, the NG pre-cooling is proposed in this work to be done with the help of HC and especially with PHC, operating in the ULTR range. The NG liquefaction bases mainly on the processes with single- and double-expansion, depicted in Figs. 4(a) and 4(b), respectively, (Stamatescu et al., 1982). A simplified presentation thereof follows. In Fig. 4(a), the NG is compressed from the ambient pressure, p_{amb}, to the final pressure, $p_{disharge}$. Subsequently, it suffers two successive pre-cooling processes, a first in a PHC-ULTR unit and a second in the Linde heat exchanger (LHE). The pre-cooling processes are followed by the single adiabatic expansion, when a unit mass is split in two complementary fractions y and (1-y), of LNG and gas, respectively. Further, the gas fraction is thermally recovered in the LHE and then is completed till unit with the y fresh NG, in order to close the cycle. In Figure 4(b), after the first expansion, taking place from $p_{disharge}$ to an intermediate pressure, p_{int}, with $p_{disharge} > p_{int} > p_{amb}$, the NG is split in two complementary fractions M and (1-M), of liquid and gas, respectively. Then, a second expansion process occurs, from p_{int} to p_{amb}, applied this time to the liquid fraction M. The consequence is M splitting in y and (M-y) fractions of liquid and gas. Further, the (1-M) and (M-y) gas fractions are thermally recovered in the LHE. After recovery, the fraction (M-y) is mixed up with the incoming y fresh NG at p_{amb}, for becoming M, and then both, M and (1-M), are sucked by the serially connected compressors, at p_{amb} and p_{int}, respectively, in order to close the cycle.

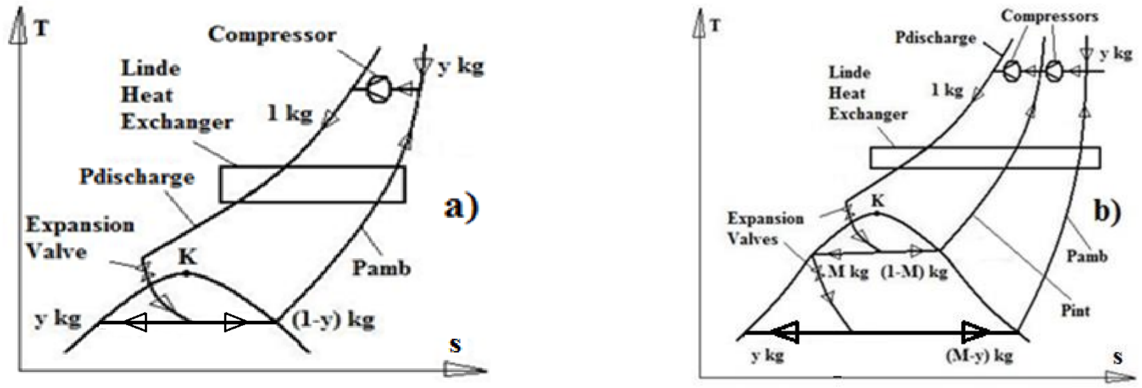


Figure 4. NG liquefaction cycles: a) single expansion; b) double expansion

5. Results Of Phc-Ultr Assisted Lng Production

The processes of NG liquefaction, assisted by PHC-ULTR and described in Figs. 4(a) and 4(b), are new. More details will follow in a work to come. The processes have been modeled with the following assumptions: i) the NG is considered 100 percent methane (CH_4); ii) the LNG cycles are supplied with the „y" gas fraction by a source found at ambient pressure and temperature, p_{supply}=1 bar and T_{ESS}, respectively; in the literature, the supply pressure is considered usually higher, p_{supply}=13.8 bar (Stamatescu, 1982), but the value of p_{supply}=1 bar is covering and closer to the global real specific work consumption of LNG production, l_s [kWh/kg liquid NG]; iii) the NG compression is considered to be three-stage, either from p_{supply} to $p_{discharge}$, Fig. 4(a), or from p_{supply} to p_{int} and p_{int} to $p_{discharge}$, Fig. 4(b); iv) the process is theoretical, and takes place without any irreversibility (e.g. cold energy losses, gas lickage), except that in the heat exchange (temperature pinch = 5 ^oC). The main input data are: a) p_{amb}= p_{supply}=1 bar, p_{int}=13.8 bar, $p_{discharge}$=69, 79 and 89 bar; b) PHC-ULTR desorber inlet (evaporator) and pre-cooling temperatures are T_{DI}=198.15 K and $T_{pre-cooling}$=203.15 K, respectively; c) the computation is done for two sets of values, coming of two T_{Mh} values, found on the isothermal T_{DI}=198.15 K in Fig. 2(c) , Table 1.
Table 1. Other important input data of LNG production model:

T_{Mh} [^oC]	T_{Mc} [^oC]	T_{ESS} [^oC]	9	18	27	36	45
85.23	-10	COP_{cPHC} [-]	3.516	2.538	1.897	1.488	1.214
113.6	0		6.232	3.489	2.330	1.706	1.341

The results of the two data sets of Table 1 are plotted in Figs. 5(a) to 5(c). T_{ESS} and LNG specific work consumption, l_s, are shown for single- and double-expansion and different $p_{discharge}$ values, in Figs. 5(a) and 5(b), against COP_{cPHC}. First, the results emphasize that the most important decrease of the specific work can be obtained by COP_{cPHC} increase. However, comparing Figs. 5(a) and 5(b), it results that T_{Mh} increase causes COP_{cPHC} increase and l_s decrease, but with diminished returns, because, as mentioned in section 3, PHC-ULTR can be applied in case of to not too high T_{ESS}, mostly. Further on, from results it becomes quite clear that increasing the number of expansions is ranked on second place for l_s decrease. And last but not least, increasing $p_{discharge}$ can decrease ls, but to a small extent. Fig. 5(c) completes the model results with output data concerning the liquid fractions „y" for single expansion, „y" and „M", for double expansion and the NG temperature prior expansion, T_{LHE}, plotted against $p_{discharge}$. Our data confirm the known behavior of these items.
The l_s values, obtained with our model, have been compared to literature data. In (Franco, 2014), after a thorough analysis, the authors conclude that an advanced NG liquefaction process consumes today about 2900 kJ/kg, or 0.805 kWh/kg. This actual figure of merit is much higher than the highest l_s value of Figs. 5(a) and 5(b), namely cca. l_s=0.5 kWh/kg. Bearing in mind these figures, the fact that our assessment is a covering one and the fact that there is room for further improvements, the PCH-ULTR assisted process gives hope in the future LNG production to achieve a figure of merit of about 50 percent out of the actual specific work consumption.

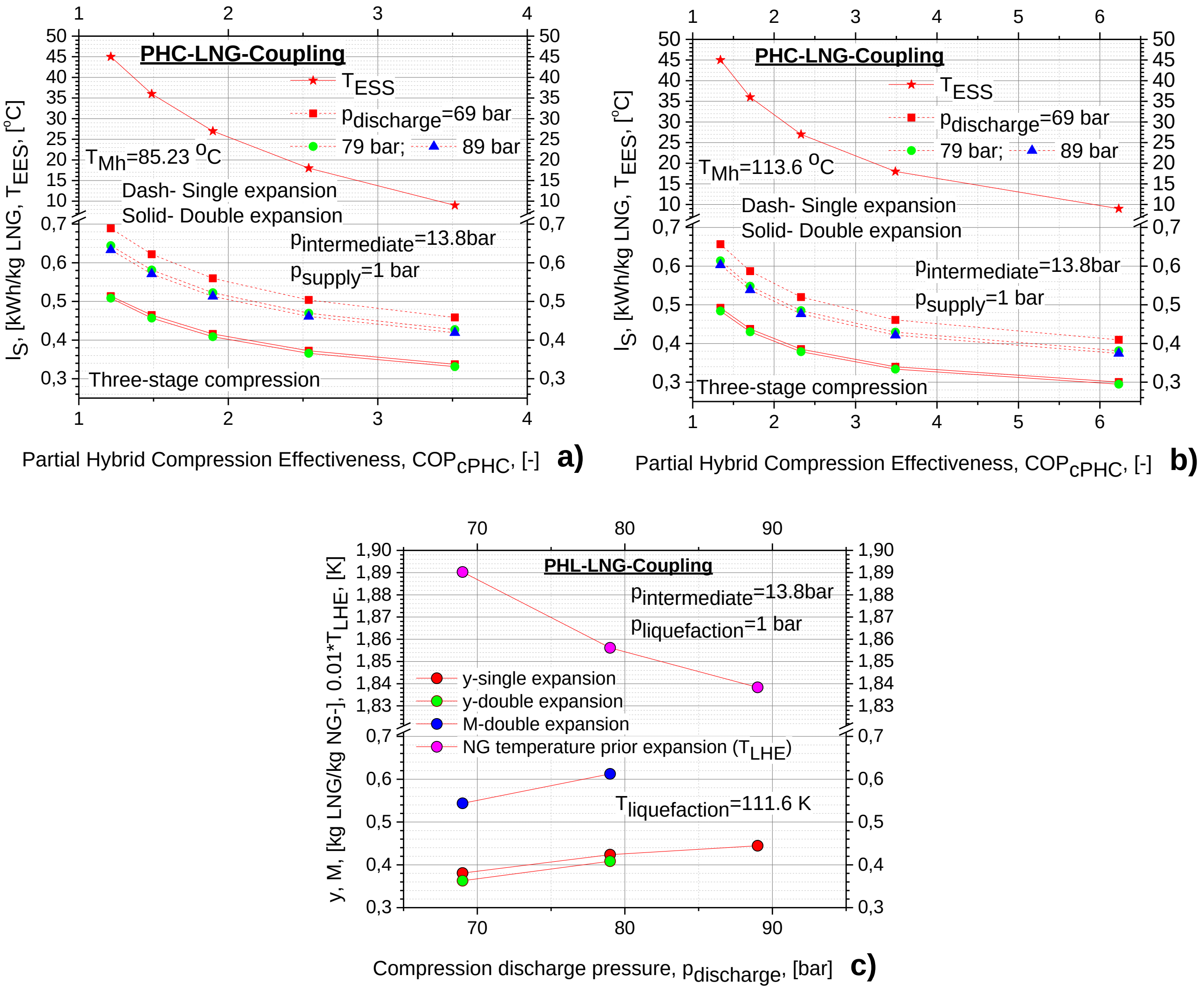


Figure 5. LNG production results with PHC-ULTR pre-cooling for (a) single and (b) double expansion; c) y, M and T_{LHE} parameters.

6. Conclusions

The PHC-ULTR, presented briefly in this paper, is a normal continuation of the already proposed HC-ULTR technology. As long as an external low-grade free heat source is available, the PHC-ULTR technology greatly improves the main operating parameters of HC-ULTR and gives hope of an increased feasibility of this technology in the future. Besides this, the research begun in this work, of a new proposed HC- and especially PHC-ULTR assisted NG liquefaction process, shows also promise in the future of LNG cryogenics.

7. References

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