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Comparison between reverse Brayton and Kapitza based LNG boil-off gas reliquefaction system using exergy analysis

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Abstract. LNG boil-off gas (BOG) reliquefaction systems in LNG carrier ships uses refrigeration devices which are based on reverse Brayton, Claude, Kapitza (modified Claude) or Cascade cycles. Some of these refrigeration devices use nitrogen as the refrigerants and hence nitrogen storage vessels or nitrogen generators needs to be installed in LNG carrier ships which consume space and add weight to the carrier. In the present work, a new configuration based on Kapitza liquefaction cycle which uses BOG itself as working fluid is proposed and has been compared with Reverse Brayton Cycle (RBC) on sizes of heat exchangers and compressor operating parameters. Exergy analysis is done after simulating at steady state with Aspen Hysys 8.6$^{®}$ and the comparison between RBC and Kapitza may help designers to choose reliquefaction system with appropriate process parameters and sizes of equipment. With comparable exergetic efficiency as that of an RBC, a Kaptiza system needs only BOG compressor without any need of nitrogen gas.

1. Introduction

Unavoidable heat in-leak into the storage tanks of Liquefied Natural Gas (LNG) carrier ships during its transportation generates the Boil-off Gas (BOG), which has to be removed to maintain the tank pressure. BOG has been used as fuel for steam engines since the start of LNG trade. From last decade, low efficient steam engines of the LNG carrier ships are being replaced by higher efficient diesel engines and the BOG is reliquefied and sent back to storage tank. This modification helps to maintain the cargo quantity and also favours environment regulations [1-3]. The refrigeration cycle of LNG boil-off gas reliquefaction system may be Reverse Brayton Cycle (RBC) [1-4] or Claude cycle [5, 6] or Kaptiza (modified Claude) cycle [7]. At least one company has developed Cascade refrigeration cycle that reliquefies the part of BOG that is not consumed in a dual fuel engine [3, 8]. The widely used refrigeration cycle is RBC. Nitrogen serves as the refrigerant in RBC as it is non-flammable and non-toxic. Gerdsmeyer and Isalski [1] explained the process technology of reverse Brayton based reliquefaction system developed by Tractebel Gas Engineering for tank capacity of 2,28,000 m³. Anderson et al. [2] discussed development activities and operating modes of Hamworthy Mark I and Cryostar EcoRel reliquefaction systems for "Qatargas 2" ships Q-Flex (2,17,000 m^3) and Q-Max (2,66,000 m^3). Hamworthy Gas System also proposed [3] an improved version Mark III, in which BOG compression is performed at ambient temperatures to minimize exergy loss in cold box and to avoid difficulties associated with cold compression. All these reliquefaction systems have different variations of reverse Brayton refrigeration cycle with nitrogen as refrigerant.

Claude refrigeration cycle has also been suggested by researchers instead of RBC with nitrogen as refrigerant. Claude has an advantage over reverse Brayton cycle that it can avoid the difficulties

associated with the formation of liquid at the exit of turbine [5, 6]. By performing dynamic simulation of LNG boil-off gas reliquefaction systems based on reverse Brayton and Claude cycle, Shin et al. [9] concluded that the former is more efficient than the latter.

2. Problem description and Objective

The studies on LNG boil-off gas reliquefaction system made so far focused on system modification keeping nitrogen as the refrigerant. If there is loss of nitrogen through compressor and expander seals, nitrogen generator has to be installed [1] or nitrogen cylinders have to be kept in reserve. This additional equipment consumes space and increases weight of the carrier. Therefore, apart from power consumption, efforts should be directed to the minimization of the number of equipment.

In the present work, a Kapitza liquefaction system (which directly compresses, expands and liquefies BOG) has been proposed and compared with RBC refrigeration based reliquefaction system. The Kapitza system proposed in this paper works as a liquefier whereas the Claude-based reliquefaction system discussed in Reference [5-7] works as refrigerator. In the Claude reliquefaction systems nitrogen provides refrigeration to BOG for its reliquefaction whereas in proposed Kapitza liquefaction system, BOG is directly reliquefied.

Apart from this advantage of having to do away with use of nitrogen, a Kapitza system reliquefies the entire BOG, while the RBC is forced to vent a small part of BOG resulting in loss of fuel gas. In RBC system BOG is cooled and condensed at higher pressure than tank pressure. So, it has to be flashed back to tank pressure creating some vapour which it has to be vented. Though this process helps to remove nitrogen content (which will reduce power consumption of reliquefaction system [4, 10]) some quantity of methane is also lost.

As all onboard systems need to economize on size and weight, it is important to determine the appropriate geometric and operating parameters which help to achieve that objective. Therefore, the effects of configuration and system parameters of LNG boil-off gas reliquefaction system ought to be evaluated to arrive at the optimum sizes of components. Exergy analysis has been adopted as the preferred thermodynamic tool in the present study because of its effectiveness in chemical and cryogenic systems [11]. Kapitza BOG reliquefier and RBC based LNG boil-off gas reliquefaction system have been analyzed and compared for the sizes of equipment and operating parameters. The effect of vent gas has been included to re-evalate the RBC system.

3. Method of analysis

3.1. Cycle configuration of comparison

Figure 1 shows an RBC based BOG reliquefaction system. BOG from the tank (stream A) is brought to ambient temperature (B) by absorbing heat from high pressure nitrogen stream in BOG preheater. BOG at ambient temperature is compressed in three stages by centrifugal compressor to a pressure 5 bar(a) (stream C), and precooled in process heat exchanger (PHX) (stream D). The heat of compression is removed in intercoolers and after cooler. Precooled BOG is liquefied in BOG condenser (stream E) by rejecting heat to the cold N_2 gas and flashed in a valve. After flashing, the condensed BOG (stream F) enters a separator from which the liquid (L) portion is sent back to the tank and the vapour portion is vented.

In RBC, the heat of compression is removed using intercoolers and after cooler. A small stream is diverted at state point 2 and enters BOG preheater to warm the BOG from the tank to ambient temperature. The remaining part of stream 2 is cooled in process heat exchanger (PHX) by rejecting heat to cold nitrogen return stream. Precooled nitrogen (stream 3) is mixed with N_2 stream from BOG preheater and stream 4 is expanded in a turbo-expander. At end of the expansion process the nitrogen stream reaches a temperature below 100 K (stream 5) and is used to condense the pressurised BOG in BOG condenser. Nitrogen stream (stream 6) is further warmed up to ambient temperature in PHX and returns to nitrogen compressor inlet.
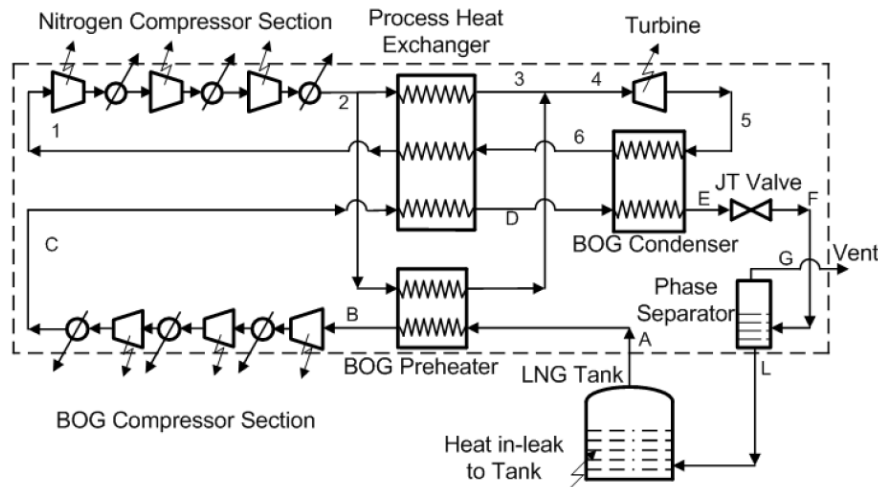
Figure 1. Reverse Brayton Cycle (RBC) based LNG boil-off gas reliquefaction system.
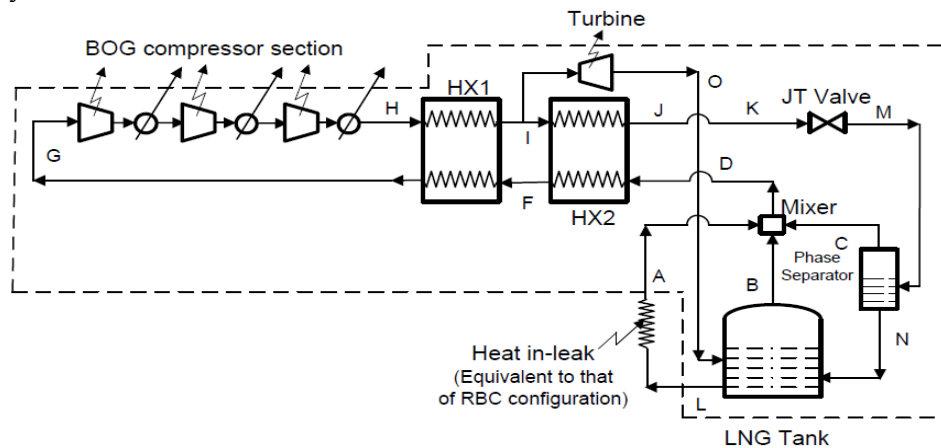

Figure 2. Kapitza BOG reliquefier (Proposed reliquefaction system).

Figure 2 shows the proposed configuration of Kapitza based reliquefaction system. BOG near ambient temperature (stream G) is compressed to about 4 to 8 bara in three stage BOG compressors and heat of compression is removed in intercoolers and aftercooler (stream H). High pressure BOG is precooled in heat exchanger 1 (HX1) (stream I) by rejecting heat to low pressure return stream. About 90% of precooled BOG is diverted to turbine. The temperature of high pressure stream at the inlet of turbine is controlled in such a way that the turbine exit condition is very near to saturated vapour (stream O). The remaining quantity is further precooled in heat exchanger 2 (HX2) and expanded to 1 bar(a) in JT valve (stream M). After flashing in JT valve, BOG enters phase separator where the separated liquid (stream N) returns to the tank and remaining vapour (stream C) returns to BOG compressors.

BOG generated in tank due to heat inleak is assumed to have a composition of 91% methane and 9% nitrogen by mole fraction [1, 4, 9]. Unlike the RBC system, the flashed gas from the top of phase separator is sent back to compressors through heat exchangers instead of venting it out. The saturated vapour at turbine exit bubbles through LNG tank in order to avoid a concentration difference in vapour streams. To simulate the heat inleak, a liquid stream of 2 kg/s is taken out from the tank, evaporated to saturated vapour by appropriate heating (the heating is equivalent to heat in-leak to the tank) and is mixed with the vapour from the top of tank and the vapour from the separator so that the final composition of stream entering cold side of HX2 is 91% methane and 9% nitrogen.

3.2. Calculation of BOG load

The typical boil-off rate (BOR) of LNG carrier is 0.13 to 0.15% per day of tank capacity [3]. Neglecting the sea conditions and the variations in ambient temperature, BOG load from tank is almost proportional to surface area of LNG tanks. The mass flow rate of BOG from tank can be calculated from the following expression [8]

$$\dot{m}_{BOG} = \frac{(BOR)(C_{Tank\ Cargo})(\rho_{LNG})}{24 \times 3600} \tag{1}$$

where BOR is the boil-off rate per day of tank capacity, $C_{Tank\ cargo}$ is the capacity of LNG carrier ship in m^3, ρ_{LNG} is the density of LNG in kg/m^3. In the present work a tank capacity of 2,66,000 m^3 (capacity of Q-Max LNG carrier ship) with a boil-off rate 0.15% of tank capacity per day is considered and mass flow rate of BOG of 2 kg/s is obtained using equation (1). (ρ_{LNG} = 435 kg/m^3).

3.3. Assumptions

(1) The systems are at steady state. (2) Heat inleak is considered only for LNG tank. It is neglected elsewhere in the cycle. (3) Pressure drop in pipelines and heat exchangers are considered negligible.

3.4. Nondimensionalisation of parameters

Flow rate of BOG represents the required size of a BOG reliquefaction system and hence any parameter of the system should be nondimensionalized with respect to the BOG load so that a designer can scale the system up or down.

Mass flowrate through compressors is nondimensionalized by mass flow rate of BOG as shown below.

$$Nondimensional\ compressor\ flow = \frac{\dot{m}_{Comp}}{\dot{m}_{BOG}} \tag{2}$$

Where $\dot{m}_{comp} = \dot{m}_{N2}$ for nitrogen cycle of RBC based system and for Kapitza based system it is equal to total flow through the BOG compressors.

To nondimensionalize the UA, the effective UA is divided by product of specific heat of BOG at 300 K and 1 atm (a) and $\dot{m}_{BOG}$ so that the dimension are matched.

Thus, for all the heat exchangers in both configurations, UAs are nondimensionalized as

$$Nondimensional\ UA = \frac{(UA)_{effective}}{\dot{m}_{BOG}\ c_{p,BOG\ (300\ K\ \&\ 1\ atm)}} \tag{3}$$

(UA)$_{effective}$ is calculated from the experimentally-determined performance (inlet and outlet temperatures) of the heat exchanger. Authors have explained this nondimensionalization process in detail in a previous work [4]. Similar nondimensionalization procedure for helium liquefaction system is explained in Thomas et al. [12]. UA in the remaining text means nondimensional UA by default.

3.5. Evaluation of Exergy Efficiency

Exergy analyses of above systems are done after simulating at steady state with Aspen Hysys 8.6$^®$, a commercial process simulator. The adiabatic efficiency of all compressors is assumed as 70% and that of turbine is assumed as 75%. The low pressure of BOG cycle of RBC based system and that of the Kapitza system is considered the same at 1.073 bar(a) [1]. The exit pressure of BOG compressor section of RBC based system is assumed to be 5 bar(a), based on data available in literature [1,3].

To study the effect of variation of UAs of heat exchangers in RBC based system, the UA of BOG preheater is kept constant at 20 and UA of BOG condenser and of the PHX are varied. In Kapitza system, the total UA of HX1 and HX2 is distributed in such a way that the turbine exit condition will not enter the liquid-vapour zone, but be very close to saturated vapour condition.

Exergy efficiency is used as a parameter for comparison between the two systems.

The specific exergy for any state point is given by $ex_i = \left[(h_i - h_0) - T_0(s_i - s_0) \right]$ (4)

where h_i, s_i and h_o, s_o are specific enthalpy and specific entropy for any state i and ambient conditions (298 K, 1 atm(a)) respectively.

Net exergy gain of the system in product output, $Ex_{out} = m_L ex_L - m_A ex_A$ (5)

For RBC based system, net exergy input to the system through work;

Not considering exergy of the vent gas, $Ex_{in} = W_{N_2\ Comp} - W_{Turbine} + W_{BOG\ Comp}$ (6)

Considering exergy of the vent gas, $Ex_{in} = W_{N_2\ Comp} - W_{Turbine} + W_{BOG\ Comp} + Ex_{vent}$ (7)

where Ex_{vent} is exergy that can be obtained from vent gas, $Ex_{vent} = \dot{m}_{vent} \times x_{CH_4} \times (CV) \times \eta_{Engine}$ (8)

where $\dot{m}_{vent}$ is mass flow rate of vent gas and x_{CH4} is the mass fraction of methane in it. CV is the calorific value of methane and η_{engine} is assumed as 0.4 in our calculation, which is the efficiency of an NG based power plant.

For Kapitza based system, net exergy input through work, $Ex_{in} = W_{Comp} - W_{Turbine}$ (9)

Exergy efficiency of the systems $\eta_{Ex} = \dfrac{Ex_{out}}{Ex_{in}}$ (10)

4. Results and discussion

The output exergy of a reliquefaction system can be increased by increasing either the exergy input to the system or by minimizing the exergy destruction occurring in the each component of the system. Any change brought to a system for improvement of its performance will result in increase of operating cost (due to increase in the exergy input) or capital cost (due to increase in the component efficiency). The exergy input is transferred to the reliquefaction system through compressors. Therefore the pressure ratio of compressors along with its operating range, mass flow rate of working fluid through the compressors for a given adiabatic efficiency will decide the exergy input.

Improvement in efficiency of each component in the system may result in minimization of exergy destruction. Improvement in efficiencies of compressors and turbine requires better design of its blade profiles and such analysis of rotary equipment is beyond the scope of this work. But UA of heat exchangers which affects its effectiveness is selected as a parameter. Addition of UA to heat exchangers decreases the exergy destruction as higher heat transfer area results in closer temperature profiles of hot and cold streams. Therefore, the effect of variation of UA of heat exchangers under different conditions of exergy input has been analyzed.

4.1. Performance of reverse Brayton based LNG boil-off gas reliquefaction

It may be observed in figure 3 that there is an optimum nitrogen mass flow rate corresponding to each range of nitrogen compressor operating pressure range. For a constant pressure ratio of 5, when the turbine exit pressure and compressor discharge pressure is high (10 to 50 bara), the exergy efficiency of the system improves. Figure 4 shows that even as the higher exergy efficiency is obtained for 10 to 50 bara or 8 to 40 bara cases, the fraction of liquid obtained is less compared to the cases of 6 to 30 bara or 4 to 20 bara.   The reason is the rate reliquefaction depends on the lowest temperature in the RBC which occurs at the turbine exit and this lowest temperature is a function of turbine exit pressure. Temperature of BOG at the exit of BOG condenser will be higher than the turbine exit temperature by a value which is equal to minimum approach in BOG condenser. To have maximum reliquefaction, the temperature of BOG at the inlet of JT valve must be near to its bubble point. The bubble point of BOG which has a composition of 91% methane and 9% nitrogen is 96 K and such a temperature cannot be achieved when the turbine exit pressure is above 6 bara. Selection of further lower turbine exit pressure is not favourable as it results in lower efficiency. It may be also observed in figure 3 that as the operating range increases, the required quantity of nitrogen reduces.

Figure 5 shows the effect of variation of UA of PHX on the performance of RBC based reliquefaction system at different pressure ratio of nitrogen compressor section with turbine exit pressure kept constant at 6 bara. It may be observed that for any pressure ratio when UA of PHX is increased the performance of the system improves. Increase in UA reduces exergy destruction in PHX and also in other components and results in overall improvement of the system. For the case of pressure ratio 6, the exergy efficiency reaches a maximum when total UA is 140 and then reduces. The reason is when UA is 140, the turbine exit has reached saturation temperature corresponding to 6 bara.

When the pressure ratio is 4 the performance of the system improves with increase in addition of UA but the exergy efficiency is always less compared to the case of pressure ratio 5. Therefore the appropriate pressure ratio for RBC based reliquefaction system is 5. The figure also shows that in order to have minimized methane content in the vent gas, the total UA of the RBC based system needs to kept above 200. Higher size of heat exchangers requires higher capital investment whereas lower pressure ratio reduces running cost of the reliquefaction plant.
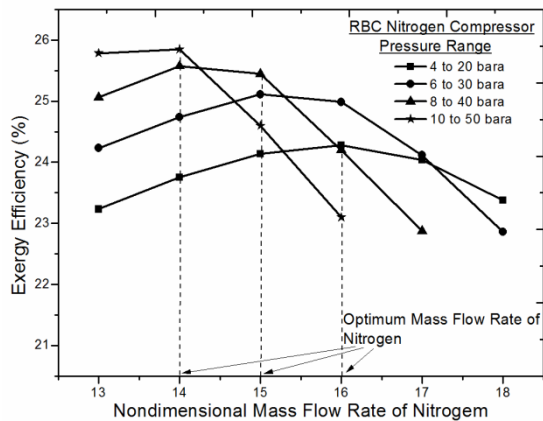

Figure 3. Effect of variation of mass flow rate of nitrogen at different nitrogen compressor pressure range on performance of RBC based reliquefaction system [UA of PHX= 140, UA of BOG condenser 20,UA of BOG Preheater = 20]
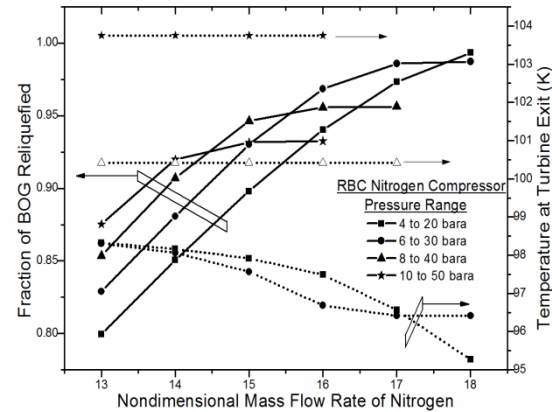

Figure 4. Effect of variation of mass flow rate of nitrogen at different nitrogen compressor pressure range on reliquefaction rate and turbine exit temperature of RBC [UA of PHX= 140, UA of BOG condenser 20,UA of BOG Preheater = 20]
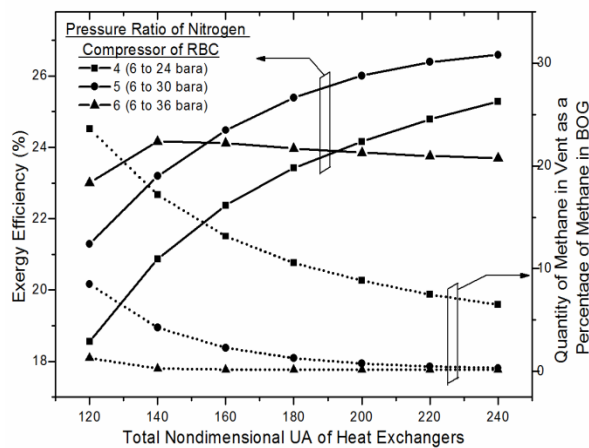

Figure 5. Effect of variation of UA of PHX at different nitrogen compressor pressure ratios on performance of RBC based reliquefaction system [UA of BOG condenser 20,UA of BOG Preheater = 20,]
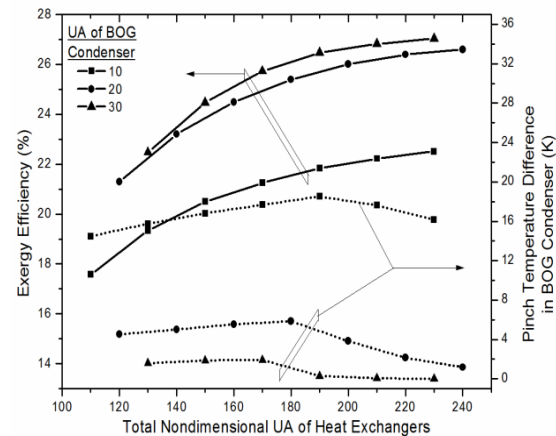

Figure 6. Effect of variation of UA of PHX at different UAs of BOG Condenser of RBC based reliquefaction system [Nitrogen compressor inlet pressure = 6 bara, Pressure ratio = 5,UA of BOG Preheater = 20

It may be observed in figure 6 that when the UA of BOG condenser is increased from 10 to 30, the performance of the system improves. A significant improvement in the performance is observed when the UA changes from 10 to 20 and only slight improvement is observed when UA changes from 20 to 30. The selection of UA of BOG condenser should be based on the minimum (pinch) temperature difference in BOG condenser and for the case of UA of BOG condenser 30, the pinch temperature difference is always below 1 K for any UA of PHX. It is not wise to design with a pinch temperature difference below 1 K as it may become zero if there is slight variation in BOG load.

4.2. Performance of proposed Kapitza based LNG boil-off gas reliquefaction system

In the Kapitza based reliquefaction system, BOG entering the reliquefaction system gets completely condensed and returns to the tank (In RBC, there is always some vent). Figure 7 shows the effect of variation of total UA of heat exchangers at different turbine mass flow rate on the performance of the system. The addition of the total UA is stopped when the increase in exergy efficiency is reduced below 2% for addition of nondimesional UA value of 5. It may be observed that the best performance is obtained when the expander flow is kept as 90% of the compressor flow. Figure 8 shows the performance of Kapitza system at different pressure ratio of BOG compressors. It may be observed that when the pressure ratio is increased the total UA requirement decreases. The pressure ratio which provides the highest exergy efficiency is 6.
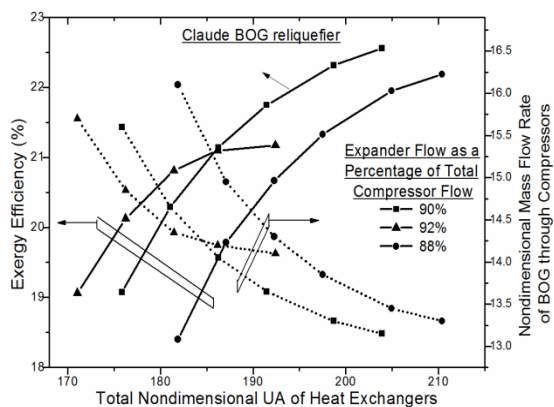

Figure 7. Effect of variation of UA of both heat exchangers at different expander flows of Kapitza BOG Liquefier [BOG compressor pressure ratio = 5, Compressor inlet pressure = 1.073 bara, Saturated vapour at turbine exit]
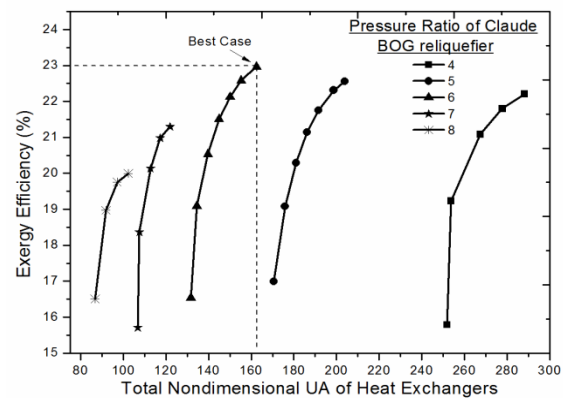
Figure 8. Effect of variation of UA of both heat exchangers at different BOG compressor pressure ratios on performance of Kapitza BOG Liquefier [Compressor inlet pressure = 1.073 bara, Saturated vapour at turbine exit]

4.3. Comparison between performance of proposed Kapitza system and reverse Brayton system

Figure 9 compares RBC with Kapitza based reliquefaction system. It may be observed that the Kapitza system reaches its best performance when total UA of heat exchangers is about 160 where as in RBC best performance is obtained when total UA is 220 (at which the mass flow rate of the vent is the minimum). Though the exergy efficiency of RBC based system is found to be slightly higher, there is exergy loss through vent gas. But in Kapitza system the entire BOG is condensed and there is no vent loss. Depending on the size of HXs the quantity that is eventually vent is 0.5 % to 5% of the methane content of BOG which enters the system. If this loss is considered in exergy calculation, then the exergy efficiency of RBC would reduce as shown in figure 9. Therefore the proposed Kapitza system has in fact a higher exergy efficiency when its total UA is close to 160.

Figure 10 shows performance of Kapitza system and RBC based system when BOG load varies from 1.8 kg/s to 2.2 kg/s with equal total UA of 160 for both systems. In operating mode of RBC based system, when the BOG load fluctuates the mass flow rate of refrigerant is controlled by inlet guide vane of turbine to mitigate the effect of load variation. Figure 10 shows that, for RBC, the variation in BOG load is controlled by changing the mass flow rate and the flow rate of nitrogen is selected in such a way that the quantity of vent lost is same as that in designed case. The exergy efficiency varies according to the flow rate of nitrogen.

Though the Kapitza system is designed for saturated vapour condition at turbine exit, it is flexible to accommodate necessary controls if the turbine exit becomes two phase or superheated vapour. As the BOG flow rate increases, the flow through the compressors also increases. As a result, net power consumption (exergy input) increases. The exergy output also increases though it is not in the same proportion as exergy input due to a higher exergy loss. Consequently, exergy efficiency decreases with increase in BOG load. The opposite happens when BOG flow decreases where exergy efficiency

increases as shown in figure 10. Turbine exit condition becomes two phase or superheated and controlling turbine flow rate will help to bring back the exit condition as saturated vapour.
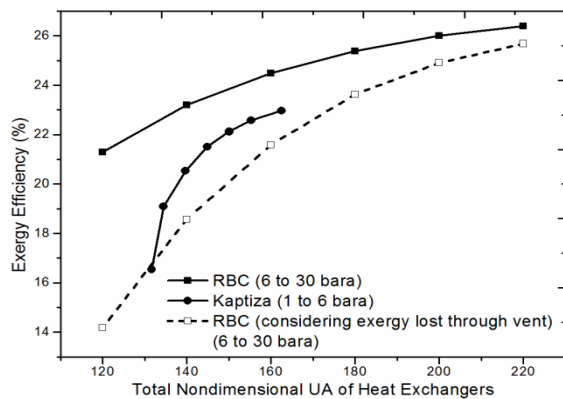

Figure 9. Comparison between performance of Kapitza BOG reliquefier and RBC refrigeration based reliquefaction systems
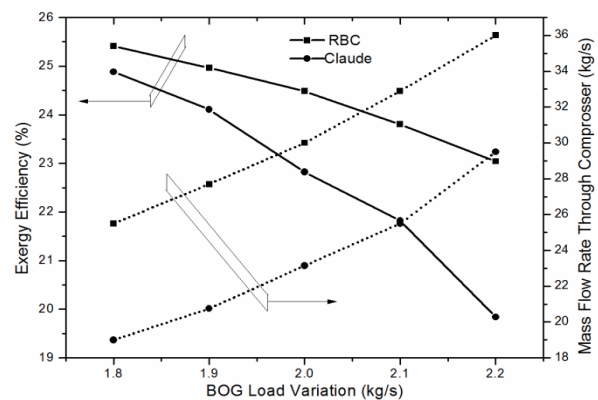
Figure 10. Effect of variation of BOG Load on performance of RBC and Kapitza based reliquefaction system [UA of both system = 160, Expander flow for Kapitza = 90%]

The advantage of Kaptiza system vis-à-vis the RBC lies in the fact that N_2 gas need not be stored in the ship during voyage. As leakage in the system is sometimes a reality, provision of storage in cylinder has to be made. RBC system has both N_2 compressor and BOG compressor while Kaptiza has only the BOG compressor. Further, venting of gas which contains methane can also be avoided in a Kaptiza system. However, because of a higher volume flow rate through the BOG compressor in Kaptiza system compared to N_2 compressor of RBC (at comparable mass flow rates, at inlet condition of 300 K and 1.073 bar(a) in Kaptiza, the gas is 9 times lighter than at the inlet of RBC compressor at 300 K and 6 bar(a)) the compressor system in Kaptiza is bulkier than that of RBC.

5. Conclusion

A Kapitza configuration for LNG boil-off gas reliquefaction has been proposed and compared with RBC system with nitrogen as refrigerant. In RBC system some exergy is lost through vent. Accounting this loss, a Kapitza system has higher exergy efficiency than a RBC for the same heat exchanger sizes. However, with a larger heat exchanger, the RBC is capable of exceeding the performance of Kapitza by a small fraction. Though the objective of reducing the number of equipment is achieved with Kaptiza cycle, the system becomes bulkier with a larger compressor.

6. References

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