"DETERMINING THE MAXIMUM LNG PRODUCTION RATE BY PROCESS SIMULATION MODELLING OF LOW TEMPERATURE NATURAL GAS SEPARATION UNIT"

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1. INTRODUCTION

The natural gas is a clean source of energy and due to this fact a continuous growth of its consumption is expected [1-6]. In some parts of the world, transportation of liquefied natural gas is the only possible way of delivering the natural gas to the final users. The consumption of LNG is rising faster than the consumption of natural gas delivered by gas pipelines. One of the reasons for gas transportation in the form of LNG is a significant distance between recipients of this gas and natural gas reserves, which are placed in remote parts of the world and are frequently have no gas pipelines infrastructure. Moreover, utilization of LNG is beneficial for environment because it is a clean fuel and its usage lowers both pollution and greenhouse gas emission into the atmosphere.

For some time now, liquefied natural gas (LNG) is treated as valuable alternative vehicle fuel since it offers some environmental, energy security and economic benefits. LNG is the cleanest of fossil fuels and during combustion produces less emission than gasoline or diesel oil. Natural gas engines meet standards for ultra low emissions vehicles. These features are among the more important advantages of using LNG as fuel. The main disadvantages of LNG vehicles are higher acquisition costs than corresponding gasoline or diesel vehicles and the fact that they can cover much shorter distance than gasoline vehicles before re-fuelling.

LNG can be obtained by natural gas liquefaction. In principle, two types of LNG plants can be distinguished:

- base load plants with constant LNG production rate - LNG plants which are the main supplying source of natural gas for its recipients
- peak shaving LNG plants, covering unequal demands for natural gas

LNG installations, which are the main supplying source of gas, are comprised of one or a few trains. The capacity of base load LNG plants is high (from $1\ 10^6$ to more than $3\ 10^6$ tonnes a year or even $4\ 10^6$ tonnes a year for one train). Portable plants, installed on the platforms or on barges with compact module structure, which allow to liquefy the natural gas from small gas deposits, are one of the types of LNG installations which work with constant, but small capacity.

The main tasks of the second type of LNG plants (peak shaving LNG plants) are natural gas liquefaction during summer time, LNG storage and LNG regasification during high (peak) gas' demands, mainly in winter time. LNG production rate of peak shaving plants is usually small, it stays within 100000 tonnes a year [4].

In the "KRIO" plant located in Odolanów, Poland, LNG is produced as an additional product (by-product). The main task of KRIO plant is the nitrogen rejection and helium recovery from natural gas. High calorific value natural gas, with methane as the main component and high quality helium are the main products. Part of nitrogen rejected from natural gas is liquefied for export and the rest of nitrogen is vented into the atmosphere as a waste gas.

The aim of this paper is to evaluate the influence of chosen process parameters, such as natural gas composition and feed gas pressure on the performance of low temperature natural gas separation unit in the KRIO plant and on LNG production rate. Particular attention has been given to the effect of feed gas pressure and to the pressure of the produced gas, taken out from cold box as well as to the kind of device used for pressure reduction on liquefied natural gas production rate.

2. DISCRIPTION OF LOW TEMPERATURE NATURAL GAS SEPARATION UNIT

The nitrogen rejection from natural gas is carried out by utilising the method of low temperature rectification, which consists in counter-current mass and heat transfer between the vapour and liquid phases. Significant differences between boiling points of methane, nitrogen and helium allow separating nitrogen from helium and methane. The main products of low temperature rectification are the so-called produced gas (high calorific value gas, with methane as main component), gaseous stream rich in helium (crude helium), liquid nitrogen and liquefied natural gas (LNG). The remaining nitrogen, separated from the feed gas, is vented into the atmosphere as a waste gas.

The low temperature separation unit of KRIO plant in Odolanów consists of network of heat exchangers (cold box), two rectifying columns (high pressure column K1 and low pressure column K2) and Joule-Thompson valves (Fig. 1). Low pressure (LP) and high pressure (HP) columns are connected by common heat exchanger, which is a boiler for LP column and a condenser for HP column. The main tasks of high pressure column are the enrichment of inlet gas with methane and helium separation from the feed gas. Gas enriched with methane is separated into produced gas (stream rich in methane) and nitrogen (waste gas).
Flow diagram of low temperature natural gas separation unit is shown in Fig. 1.

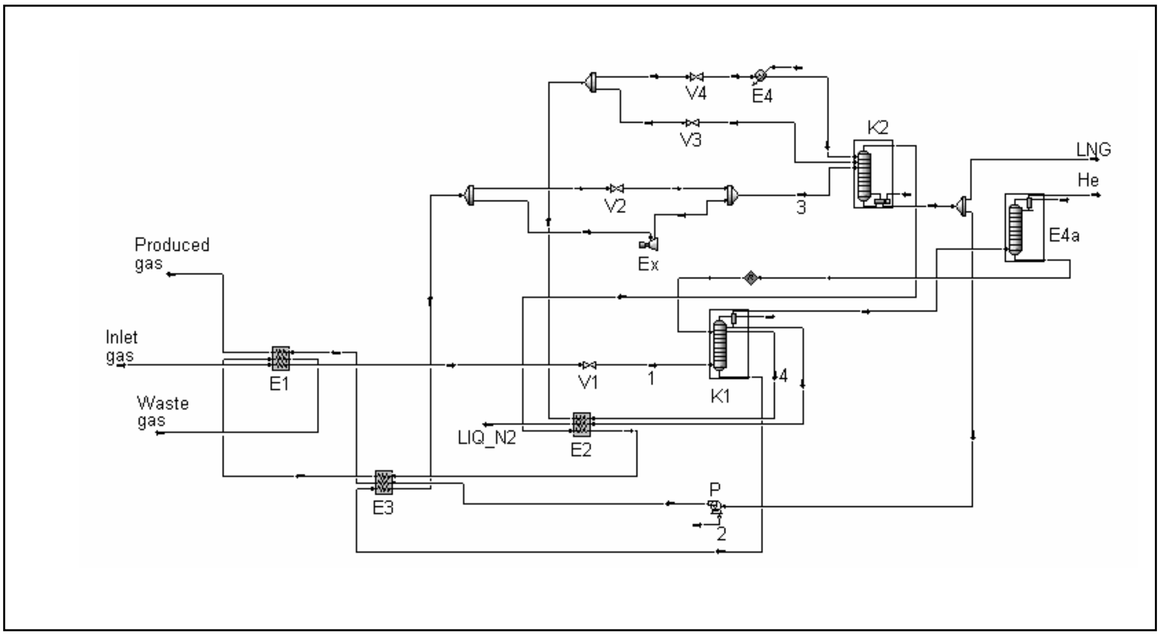

Fig. 1 Low temperature natural gas separation unit flow diagram

Clean natural gas is cooled in the heat exchanger E1, placed in the cold box and then it is introduced into Joule-Thomson (J-T) valve V1, where gas pressure is decreased. The decrease in the temperature of inlet gas in heat exchanger E1 is a result of heat transfer between inlet gas, produced gas and waste gas. After pressure reduction in J-T valve (V1), the stream temperature decreases below the temperature of condensation. Two-phase stream (1) is put into the bottom part of high-pressure column K1. Rich liquid (with high methane content), poor liquid (containing mainly nitrogen), liquid nitrogen and the crude helium are the main products of high-pressure column. After preliminary cooling and pressure reduction in the valve V2, rich liquid is fed into low-pressure column, where the final separation into nitrogen and methane takes place. Streams of poor liquid after pressure reduction in valves V2 and V3 are introduced into the top of low-pressure column K2 as a reflux.

The products of low-pressure column K2 are liquid methane and gaseous stream rich in nitrogen (waste gas). Liquid methane (containing less than 4 % mole nitrogen) is pumped to the higher pressure and then it is fed into cold box E1, where it exchanges the heat with feed natural gas stream. High calorific produced gas at room temperature, leaving the cold box, is then compressed and introduced into the system natural gas pipelines. Part of liquid methane (liquefied natural gas –LNG), taken directly from the bottom of low-pressure column, is a by-product of low-pressure column K2. The gaseous stream rich in nitrogen is passed through the heat exchangers E2, E3 and E1 and then it is piped away into the atmosphere as a waste gas.

Currently all energy needed for natural gas separation in low temperature unit is provided by pressure reduction of the natural gas on the Joule-Thompson valves. After modernisation, that is after Joule-Thomson valve V2 replacement with liquid expansion turbine (Ex – Fig.1), additional energy will be available and the cooling capacity of low temperature unit will be higher.

Nowadays the work regime of low temperature natural gas separation unit is different from design data. It is caused by lower pressure of inlet gas and lower concentration of nitrogen in the inlet natural gas.

The change of such parameters as the nitrogen concentration and pressure of the inlet natural gas have a great impact on the efficiency of low temperature natural gas separation process.

The main objectives of this work are to evaluate the effect of gas composition and gas pressure on performance of nitrogen rejection unit and to assess the possibility of LNG production as a by-product with as high production rate of LNG as possible. Analysis has been performed for actual flow sheet and for modernised technological flow sheet of the unit.

3. SIMULATION MODELLING

In order to determine the maximum LNG yield from low temperature unit of KRIO plant, the two simulation models have been developed [7]:

- The simulation model of actual (current) low temperature unit, based on the process design information and real plant performance data taken during the plant operation.
- The simulation model of modernised low temperature unit after replacement of the J-T valve (V2) with liquid expansion turbine.

The simulation models have been prepared by using the Hysys Process software package (Hyprotech, Calgary).

Building the KRIO plant simulation model consist in selection from Hysys library the proper unit operation models, describing the heat and mass transfer taking place during the process, defining the streams, characterising heat exchangers, columns and other plant equipment and choosing the proper set of independent variable. Developed simulation model makes it possible to study the plant performance at changing operating parameters.

The process simulation models have been developed under the following assumption:

- Steady state heat and mass transfer mode
- Peng-Robinson EOS property package used for modelling one- and two phase systems
- Heat exchangers are characterised by duty, heat transfer area, heat transfer coefficient, UA values (quotient of heat transfer area and heat transfer coefficient), minimal temperature difference between the cold and hot streams, pressure drop, cold losses (heat leak)
- Intensity of heat transfer is characterised by heat exchanger UA values
- Cold losses are proportional to heat duty and distributed evenly along the heat transfer area
- Columns are characterised by geometrical parameters (diameter, height, number of trays and their geometry, trays efficiencies, parameters characterising the column internals, like weir height, downcomer clearance, number of flow paths and others), operational parameters (pressure, temperature, flow rate of streams, pressure distribution along the column, reflux ratio defined as molar ratio of liquid returning from condenser into the column top over the total flow of the liquid and vapour product).
- Mass transfer in the columns is described by using theoretical as well as real trays, characterised by tray efficiency
- Cold losses from the columns are determined by using internal Hysys detailed heat transfer model

The column performance has been checked by hydraulic calculation and by evaluating such parameters as flooding coefficient, downcomer backup, weir liquid loading, pressure drop per tray and total pressure drop.

Process simulation modelling has been done in two stages. The scope of the first stage was to predict the current operating performance of KRIO plant with as high accuracy as possible by adjusting the model parameters. Such model parameters as trays efficiency of rectifying columns, cold losses from the whole system and heat exchanger UA values were adjusted on the basis of testing calculations.

Process simulation model with fitted model parameters has given quite good prediction of KRIO plant performance and then, in the second stage it was used to predict the plant performance at different set of operating parameters and different plant arrangement (with J-T valve or liquid expansion turbine for pressure reduction of rich liquid).

4. RESULTS OF SIMULATION

The process simulation model computations have been performed for the following set of parameters:

- Nitrogen content in the inlet feed natural gas from 33 % to 38 % mole
- Inlet pressure of natural gas from 5.0 MPa to 6.0 MPa
- Inlet flow rate of natural gas from 90 000 m^3(n)/h to 130 000 m^3(n)/h

The computation has been done by using temperature difference at the warm end of heat exchangers as model parameters.

The degree of separation of natural gas with high nitrogen content depends on many operating parameters. Inlet gas pressure and composition are one of the most important parameters, having a big influence on plant performance. Inlet gas pressure determines the cooling capacity of unit and gas composition (particularly nitrogen content) determines the quality of produced gas and the degree of methane recovery. As it will be shown, the produced gas pressure (at the outlet of cold box) also determines the unit performance.

The quality of the main final products of nitrogen separation unit (produced gas with high methane content, preferably over 96 mol % and wasted nitrogen with as low as possible methane content, lower than 1 mol %) depends also on the conditions and operating parameters of rectification process, such as temperature and pressure of inlet and outlets streams, reflux number and type of column’s trays.

The production rate of LNG depends mainly on the degree of utilisation of available cold and on cooling capacity of low temperature natural gas separation unit, which is related to the method used for pressure reduction.

4.1 The effect of nitrogen content on methane recovery

Decreasing amount of nitrogen in feed gas has the influence on product quality and as the consequence on the methane recovery. Lower amount of nitrogen in the feed gas means lower reflux in low pressure column, higher temperature in column K2 and lower methane recovery.

“KRIO” plant in Poland was design for natural gas containing 40 to 42 mol % of nitrogen. Now nitrogen concentration in the natural gas fed into the unit stays within the range of 33 to 38 mol %.

Model simulation has been performed for evaluating the effect of nitrogen concentration on methane recovery. On the basis of the results of simulation modelling it can be concluded that decreasing nitrogen content in the feed gas from 38 to 33 mol % does not have a big influence on methane recovery, which decreases only slightly from 99.6 % to 99.2 %. Farther decreasing the nitrogen concentration (to values lower then 30 %) leads to substantial reduction of methane recovery (lower than 97 %) and to high methane losses.

4.2 The effect of inlet gas pressure and kind of expansion device on LNG production rate

The LNG mass flow rate depends on many parameters, such as inlet natural gas pressure, gas composition, cold losses in the entire unit (in the cold box and in the columns), the degree of heat recuperation in the heat exchangers (in the cold box), the method of pressure reduction (J-T valve or liquid expansion turbine) and the degree of pressure reduction.

The LNG mass flow rate may be maximised by minimising the cold losses from the unit (from cold box and columns), decreasing the temperature difference at the warm end of heat exchangers and choosing the proper operating parameters or by the plant modification (replacing the J-T valve for pressure reduction of rich liquid with liquid expansion turbine).

On the basis of simulation results the following conclusion can be drown:

- LNG flow rates increases with the increase of inlet gas pressure (Fig. 2)
- Owing to the replacement of the J-T valve with liquid expander the LNG flow rate increases more then two times – Fig. 2
- LNG flow rate can be increased due to the decrease of the cold losses (by decreasing the temperature difference at the warm end of heat exchanger, which results in the increase of heat recuperation) –Fig.3.

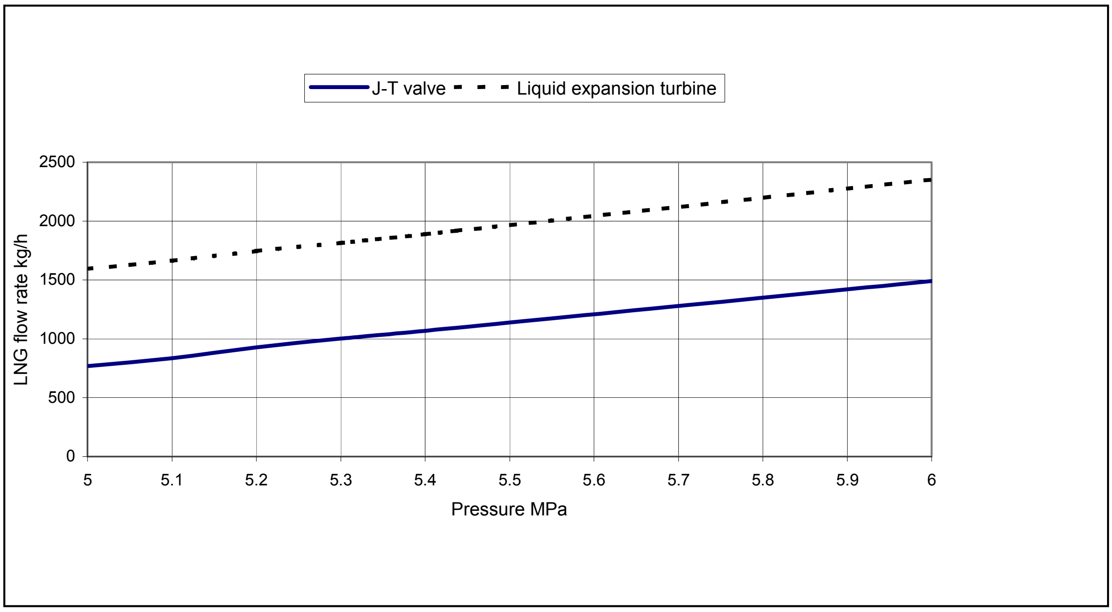

Fig. 2 Effect of inlet gas pressure and the type of expansion device on LNG production rate (nitrogen concentration in the feed gas 38 mol %)

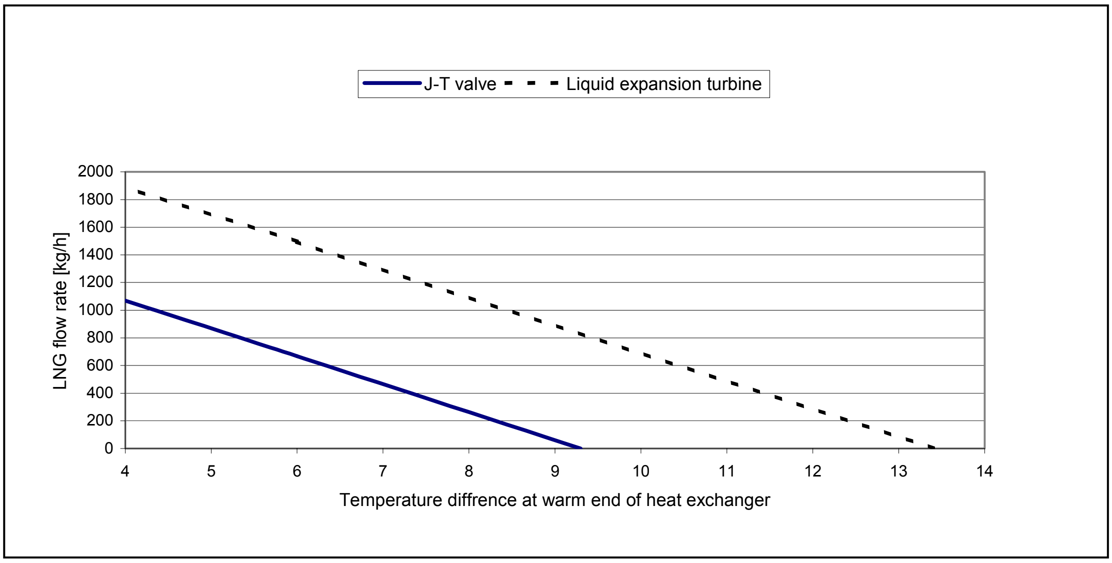

Fig. 3 Effect of temperature difference at the warm end of heat exchanger and type of expansion device on the production rate of LNG (inlet gas pressure 5.4 MPa)

4.3 The effect of produced gas pressure (at the outlet of cold box) on LNG production rate

Pressure of the produced gas is also an important parameter, in determining the production rate of liquefied natural gas. However this parameter has indirect effect on the LNG production rate. Pressure of produced gas has direct effect on the performance of heat exchangers, where cooling of natural gas takes place.

Inlet natural gas before being inserted into rectification column K1 is chilled to low temperature. The fall of inlet gas temperature is gained by the heat exchange process, which proceeds in heat exchanger E1 (Fig. 1), thanks to the heat exchange between the inlet natural gas, the stream of liquid methane and waste gas stream.

The amount of heat Q, which is exchanged between the hot and cold streams, depends on heat exchanger UA value and the temperature difference between the streams (ΔT).

The heat exchange can occur when the difference between streams' temperatures in any part of heat exchanger is equal or bigger than minimum temperature difference. The point in which the temperature difference is equal to minimum temperature difference is called 'pinch point'. For cryogenic heat exchangers minimum allowable temperature difference should be in between 3 to 5 deg [8].

Plate heat exchangers (those which are in the cold box of low temperature's separation unit) have high heat exchange area, and due to this fact they allow to perform the heat exchange process with small temperature difference. However, the temperature difference has to be equal or higher then minimum allowable temperature difference. If the temperature difference is 0, the heat exchange process will be stopped. In this case, curves, describing the dependence of temperature profile of hot and cold streams as a function of their enthalpy ($T = f(H)$), cross together. Temperature crossovers of hot and cold streams profiles is prohibited by the second law, which determines the direction of heat flow from hot to cold stream.

The course of curves, which show the temperature's change of hot and cold streams as a function of their enthalpy, depends on those streams' parameters.

In the case of analysed heat exchangers in the cold box, the course of those curves depends on hot and cold streams' pressure. The bigger pressure difference between cold and hot streams, the bigger the distance between the curves $T=f(H)$. For established inlet gas pressure, the higher is the temperature difference, the lower is the pressure of liquid methane behind the pump (P) and the lower is the pressure of the gas produced. When the pressure of liquid methane behind the pump is too big, the temperature difference is reduces beneath allowable value.

The pressure of produced gas taken from the cold box has the influence on the production rate of liquid nitrogen and LNG.

Using the developed computer simulation of low temperature natural gas separation unit, the highest acceptable pressure of liquid methane stream behind the pump (P) was determined in the function of amount of liquid nitrogen (Liq_N2) taken from column K1 and the amount of LNG, taken from column K2.

The analyse of simulation calculations leads to the following conclusions:

- Acceptable, highest liquid methane pressure behind the pump (P) is being reduced when the production rate of liquid nitrogen increases. At the inlet gas pressure 5.25 MPa, the increase of the production rate of liquid nitrogen from 270 m^3(n)/h to 1010 m^3(n)/h necessitates reduction the liquid methane pressure behind the pump (P) from 1.84 MPa to 1.71 MPa so about 0.13 MPa.
- At the inlet gas pressure 5.4 MPa, increasing the liquid methane pressure behind the pump (P) from 1.6 MPa to 1.9 MPa, results in decrease of the LNG production rate from 1250 kg/h to 970 kg/h. Farther increase in the liquid methane pressure up to 2 MPa, causes the decrease of minimal temperature difference below the acceptable value (Fig.4). In this case some perturbation in plant performance may be expected.
- Acceptable, the highest liquid methane pressure behind the pump (P) depends on inlet natural gas pressure

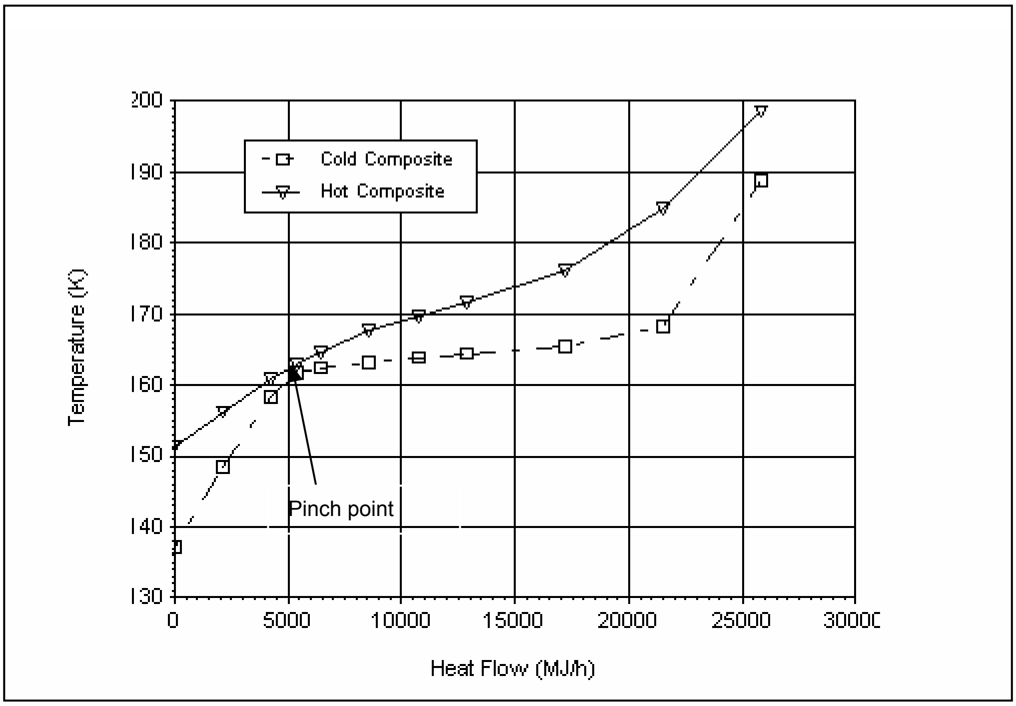

Fig. 4 Dependence of hot and cold temperature on heat flow for inlet gas pressure 5.4 MPa and outlet produced gas pressure 2.0 MPa (pinch point at minimal temperature difference equal 1 deg)

5. FINAL CONCLUSION

Natural gas separation is a complex process. Performance of low temperature natural gas separation unit depends on heat exchange process, taking place in heat exchangers, simultaneous mass and heat transfer processes taking place in rectifying columns and on expansion process.

Changing the operating parameters such as inlet gas pressure, inlet gas temperature and gas composition (particularly nitrogen content) has a big influence on plant performance. Decrease in the inlet natural gas pressure causes the decrease of Joule-Thompson effect (increase the temperature of stream entering the HP column) and lower purity of products (higher nitrogen content in liquid methane and higher methane content in waste nitrogen gas). The effects of lower content of nitrogen in inlet natural gas are higher temperature in column, lower reflux in LP column (because of lower amount of nitrogen in the feed gas) and lower purity of products.

The simulation calculations of low temperature natural gas separation unit have shown that the liquid methane pressure behind the pump (P) and the produced gas pressure (at the outlet of cold box) are very important parameters which describes the possibility of heat exchange in cold box. To assure the proper work of low temperature natural gas separation unit, liquid methane pressure behind the pump cannot be higher then the highest acceptable value with which the temperature difference between heat exchanging streams is equal to the minimum, allowable temperature difference.

Low temperature natural gas unit modernisation consisting in J-T valve replacement with liquid expansion turbine will substantially improve the unit performance. Joule-Thompson expansion leads to dissipation of energy, while liquid expansion turbine generates power. As a result of increased cooling capacity of the unit, even at the lowest inlet gas pressure (5 MPa), the LNG production rate will be higher than maximum LNG production rate attainable presently.

However in order to reach desirable goals such as maximum methane recovery, minimum energy consumptions, minimum cost and greenhouse gas emission as low as possible it is necessary to make optimisation analysis of low temperature natural gas separation unit.

The goals of optimisation analysis should be:

- Maximum methane recovery (as small as possible methane emission into the atmosphere)
- Maximum production rate of liquefied natural gas or liquid nitrogen
- Minimum external energy consumption (as high as possible produced gas pressure at the outlet of cold box)

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