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High temperature gas heat pumps to recover industrial waste heat

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Table of Contents

Table of Contents 0
Background 2
Aim 3
Methods 6
Results 9
Conclusions 12
References 13

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Background

During the last decades large efforts have been done to improve energy efficiency of the equipments that uses fossil fuels. Today, energy prices and environmental constraints are one of the main issues for the industrial end-users. There is a strong need to further improve energy efficiency. High temperature waste heat has been considered in priority because recovering and reusing high temperature wastes allows to reduce substantially the energy consumption of the process.

As the cost of energy keeps on increasing, industrial actors are looking for new sources of energy efficiency improvement. Large energy savings can be achieved through the efficient use of low temperature waste heat in lots of sector within the industry.

Large amounts of heat need around 100°C and large amounts of low temperature waste heat available

Around 70% of the energy used in the European industry is dedicated to heating. As demonstrated by the EcoHeatCool project [1], a large part of the heat required for is lower than 150°C. The main industrial sectors concerned by low temperature needs are chemicals, food industry, pulp and papers.

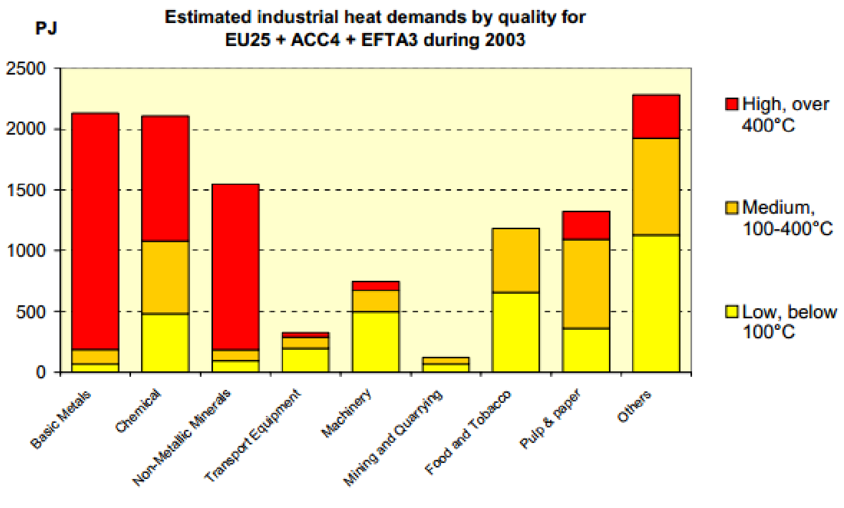

Figure 1 - Heat needs for the European industry (source: EcoHeatCool project[1])

In industrial factories, there is a large amount of waste heat at 50°C-80°C in the form of waste gases (mostly moisturized air from dryers, compressors, or other process gases), liquids (cooling water, distillers residuals, or other process liquids) and also solid wastes. It represents more than 40 TWh in the French industry and about 500 TWh in the Europe industry. However, to be able to recover this energy usually left over, specific technologies are required. Industrial high temperature heat pump can be used to recover and reuse this wastes at higher temperature.

Historical use of gas heat pump in the industry

A few gas heat pumps have been installed in France in the 1980s for industrial purpose. For example, one was aimed at recovering waste heat from a brewery process and to use it. Another one was designed to improve energy efficiency on plaster drying.

In both configurations the exhaust gases and the cooling water from the engine were recovered allowing to increase the COP (coefficient of performance). The solutions implemented on the brewery site allowed a 44 % fuel savings (based on measurements) for a useable temperature of air around 65°C.

The fluids used in the two gas heat pumps were: R-12 (CFC), R-22 (HCFC) and R-500 (HCFC). Since 1989, Kyoto protocol bans the use of R-12. Moreover, the HCFC fluids have been mostly phased out in new equipments under the Montreal protocol. However high temperature was not reachable for those fluids (critical temperature is under 105 °C).

Due to fluid issues, cheap energy and problems encountered with the reliability of the engines, industrial gas heat pumps have not emerged yet. But today, increasing energy prices, developments of new refrigerant gases and improvements in gas engine quality, have renewed interest on gas engine heat pumps in the industry.

Aim

Design for energy integration optimization

Besides relevant integration of the heat pump in the industrial process, the integration of the heat fluxes in the heat pump systems itself must be taken care with caution.

When using a standalone engine, the gas engine is cooled by water entering in the engine at 70°C temperature and leaving the water jacket at 90°C. It is usually cooled by cooling towers. Flue gas leaves the engine at around 350°C - 450°C (depending on various engine settings). This heat directly leaves the engine through the stacks. Several combined heat and power manufacturer have design heat recovery systems to heat water from those sources.

For industrial heat pump application, heat recovered from the engine can be used in several places: upstream of the condenser, downstream of the condenser, or upstream of the evaporator. Heat recovered can also be used directly in the refrigerant cycle or for another heat stream. Pinch method or exergy analysis tools can also help for choosing the best configuration. Current works are on way to be able to take into account gas heat pumps in pinch analysis models.

To reach high temperatures (above 100°C) it was found that the best configuration was to use separately the energy from the cooling water of the engine and the energy from the fumes (cf. Figure 2). Cooling water energy is dedicated to preheat the hot source before entering in the condenser heat pump whereas engine fumes energy is used to heat the hot source so as to reach the aimed hot temperature.

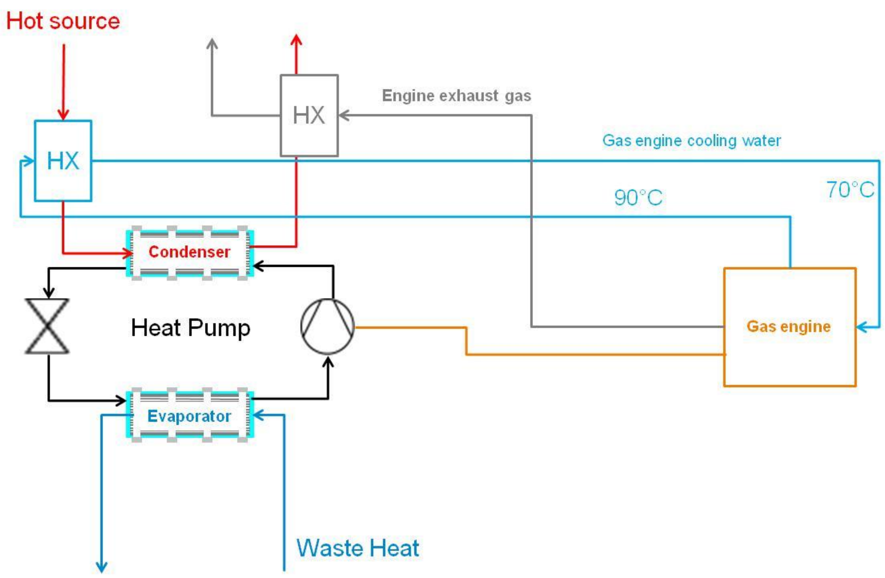

Figure 2 - Integration of an industrial gas heat pumps in a process

From a specific industrial process flow diagram, a numerical model was designed to evaluate the performance of the whole system to heat a hot source from waste heat energy. The model (cf. Figure 3) is based on the commercial DYMOLA library. The PID controllers adjust the gas engine load in order to reach the set point temperature.

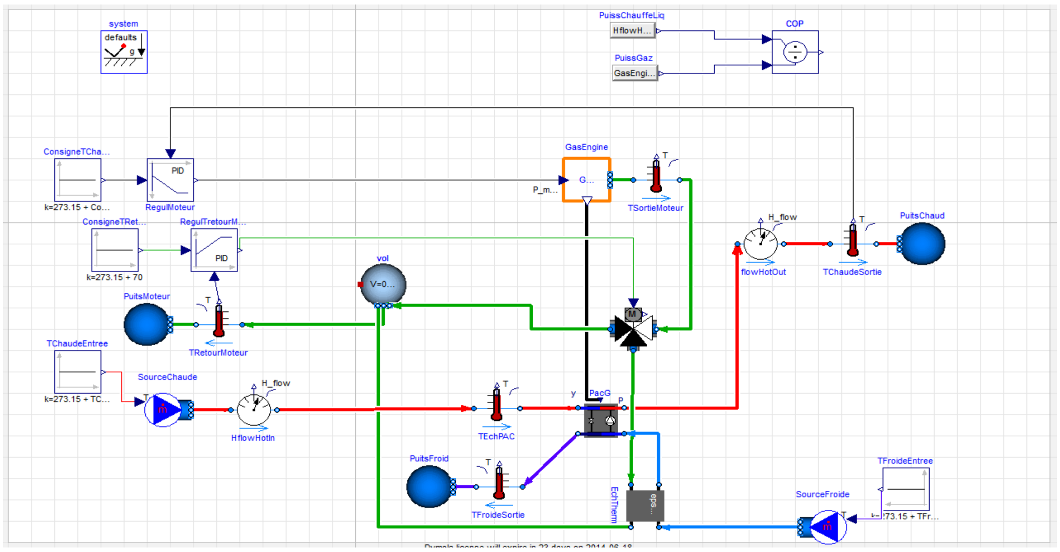

Figure 3 - Example of the integration model simulation

COP is calculated according to the following formula:

$$COP = \frac{\Delta P_{hot\_source}}{P_{gas}} = \frac{(P_{condenser} + P_{water\_hx} + P_{fumes\_hx})}{P_{gas}}$$

Where:

- ΔP_{hot_source} is the power transmitted to the hot source through the whole systems,
- P_{gas} is the natural gas power consumed in the gas engine,
- $P_{condenser}$ is the power transmitted to the hot source through the condenser,
- P_{water_hx} is the power transmitted to the hot source through the heat exchanger of the cooling water,
- P_{fumes_hx} is the power transmitted to the hot source through the heat exchanger of the engine fumes.

Methods

Technical design of a high temperature gas heat pump

The integration of the heat recovered from the engines strongly influences the performance of the whole system and therefore the COP. GDF SUEZ is involved in a collaborative project named VALENTHIN (VALorisation des ENergies THermiques INdustrielles) which is aimed at developing new routes to recover and valorize waste heats. Special integration is one of the top priorities of development in the project. The goal is to increase the power delivered by the heat pumps and also to maximize the temperature at the condenser

Several works are currently taking places to allow efficient systems working at highest temperatures:

- Investigation on new fluids
- Optimization of heat recovery on the gas engine waste heats

Absorption heat pumps

Absorption heat pumps applications also exist where the absorption machines are fired by waste heat. Absorption pumps machines also transfer heat from a low temperature to a high temperature. In a typical absorption heat-pumping application, waste heat at low temperature is delivered to the evaporator, and prime heat at high temperature is delivered to the generator. Vapor absorption refrigeration systems using water-lithium bromide pair (ammonia water systems also exists) are largely used in large capacity air conditioning systems, they can be converted into heat pump to recover waste heat. A 90°C temperature can be obtained with those systems driven by the combustion of natural gas or high pressure steam.

Gas heat pump

A gas heat pump usually consists of a vapor compression heat pump with a gas engine. It is driven by a gas fuelled internal combustion engine instead of an electric motor. Generally, the gas heat pump system mainly contains two parts: the heat pump itself, which includes a compressor, a condenser, an expansion valve and an evaporator, and the gas engine system.

Two configurations can be used (cf. Figure 4). The first configuration is the use of an open compressor that is directly moved by the engine shaft. The second one is the use of a combined heat and power device to produce electricity. Electricity, that is used in the electrical engine to drive the compressor.

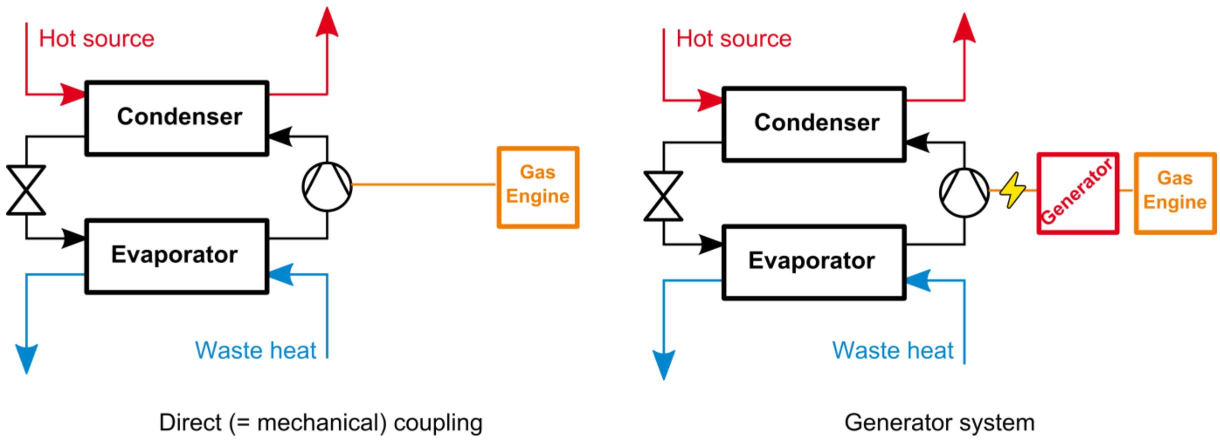

Figure 4 –Direct and generator configurations

In both configurations, several heat sources from the engine are available: cooling water, cooling oil, and exhaust gases. A special attention has to be paid on the design of the heat pump to accurately use those energy sources in order to increase the COP of the whole system.

Working fluid for high temperature gas heat pumps

For high temperature vapor compression heat pumps, the choice of the refrigerant fluid is a key parameter. The refrigerant has to offer the best energy performance, the lowest cost, the lowest impact on environment and to guarantee the safety of the machines. Most of those features are directly linked with the chemical and thermodynamic properties. Several studies [2] have compared the various refrigerants from different standpoints such as environmental (ODP, GWP, safety group, critical temperature) and performance concerns.

Access to physical properties is available through both commercial and open source libraries. We have used the properties of several conventional fluids (cf. Figure 5) obtained with the open source library Coolprop [3].

Type	ASHRAE number	Chemical Name	ODP	GWP	Critical temp. [°C]
HFC	R-134a	1,1,1,2-Tetrafluoroethane	0	1430	101.1
HFC	R-245fa	1,1,1,3,3-Pentafluoropropane	0	1030	154.1
HFO	R-1234yf	2,3,3,3-Tetrafluoropropene	0	4	94.7
HCFC	R-123	2,2-Dichloro-1,1,1-trifluoroethane	0.02	77	183.7
HC	R-600a	Isobutane	0	3	134.7
Natural	R-717	Ammonia	0	0	132.4

Figure 5 – Selection criteria with physical properties of several refrigerants

Critical temperature gives an overview of the maximum temperature that the fluid can reach in the heat pump (without taking into account possible gas deterioration). Mechanical COP obtained has been calculated (cf. Figure 6) for a single-stage cycle with the help of Coolprop library. A common rule of thumb is that the optimal COP is obtained for a condensation temperature of the fluid lower than around 30°C of the critical temperature. It is observed that for a given condenser temperature, large variation of COP can be obtained according to the various fluids.

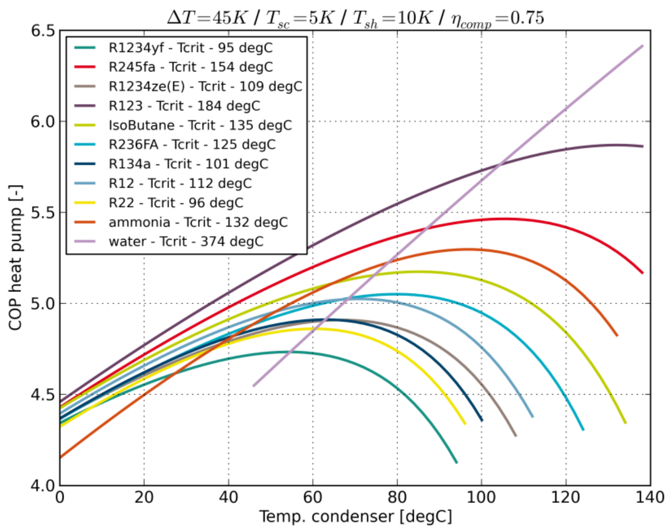

Figure 6 - Mechanical COP calculated for several fluids (CRIGEN calculations)

The inconvenient of those fluids is the high GWP. CO_2 is also often used as a refrigerant but is not adapted to large machine working at high temperature.

Future developments are therefore required to reach high temperature and high performances (such as one obtained with the R-123) but with low impact on the environment (low GWP) and safety compliant. Industrial partners within the VALENTHIN consortium are specifically working on that topic.

Results

A parametric study has been carried out to calculate the maximum value of COP reachable with a fixed hot source temperature set point (up to 110°C). The performance of the fluid cycle is directly linked with the difference of temperature between refrigerant condensation and vaporization. Therefore the difference between the temperature of the waste heat and the set point temperature of the hot source (cf. Figure 7) has a major influence on the performance of the whole system.

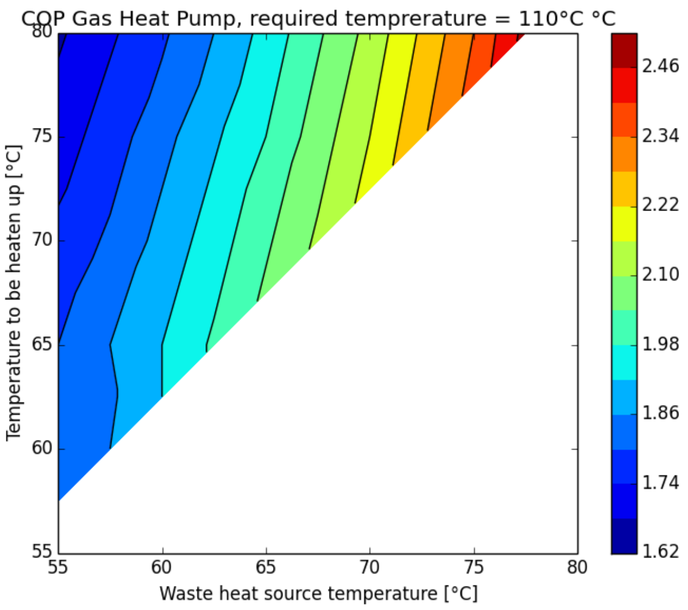

Figure 7 – Calculated COP of the whole system

The temperature of the hot source before entering the heat pump system also slightly influences the COP. When the hot source temperature gets closer to the cooling water circuit temperature not all the cooling water heat can be recovered for heating the hot source.

Example of gas heat pump setup in the chemical industry

Chemical industry can offer great opportunities of gas heat pump implementation in the process in order to increase energy efficiency. In the example presented here, it is shown how a heat pump and the heat produced by a gas engine can be used to decrease energy consumption of a distillation column by about 55%.

In a distillation column (Figure 8), it is necessary to condense the vapor produced at the top in order to extract first product (product B on Figure 8) while part of the liquids produced at the bottom have to be heated back in order to be reintroduced in the distillation column. In this example, the cooling fluid enters into the condenser at 63°C and leaves it at about 53°C. In the mean time, the heating fluid at the base of the distillation column enters into the reboiler at 95°C and leaves it at about 105°C.

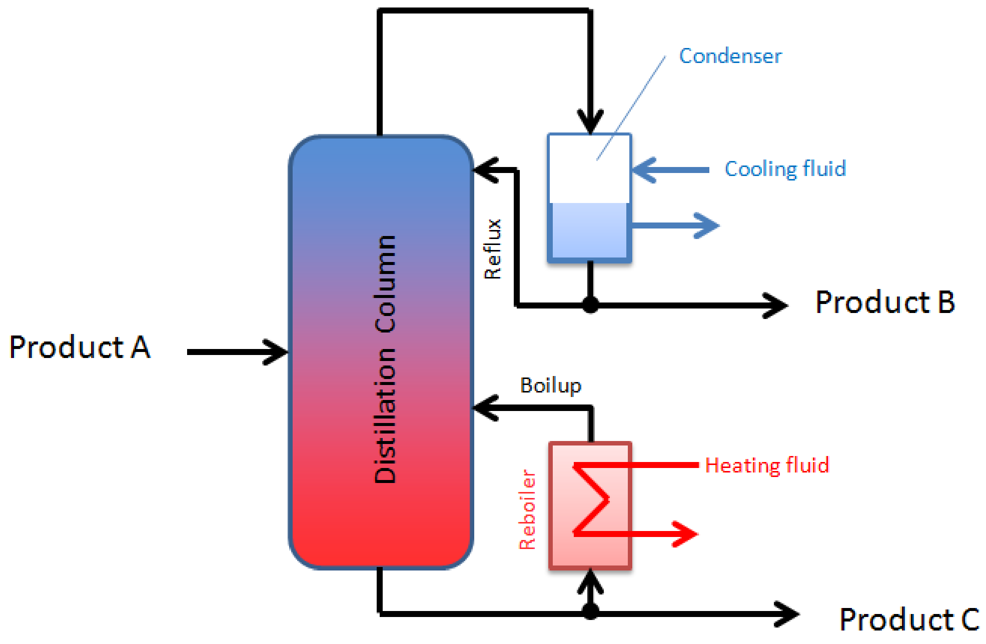

Figure 8 - Distillation column (initial configuration)

In the current configuration, steam is used to heat up the fluid in the reboiler. In the studied configuration, the cooling fluid flowing out of the condenser will be used to increase the temperature of the heating fluid before it enters the reboiler. As a gas engine is used to drive the heat pump, it is possible to increase the efficiency of the system by taking advantage of the heat produced by the cooling of the gas engine and by the heat remaining in the combustion products. The engine selected has the following power distribution between electricity production, and the heat of combustion products and cooling circuit: 41%, 26% (considering cooling combustion products down to 120°C) and 16%.

The optimized setup is shown on Figure 9.

Water is the engine cooling fluid. It leaves the engine at 90°C and must return at 82°C. These temperatures are lower than those of the fluid used in the reboiler (95°C<T<105°C). So, it is not possible to use it to heat up the heating fluid of the distillation column. However, it can be used to heat the cooling fluid before it enters the heat pump in order to increase the COP. On the contrary, thanks to the high temperature of the burnt gases, the burnt gases/heating fluid heat exchanger can be placed between the heat pump and the reboiler.

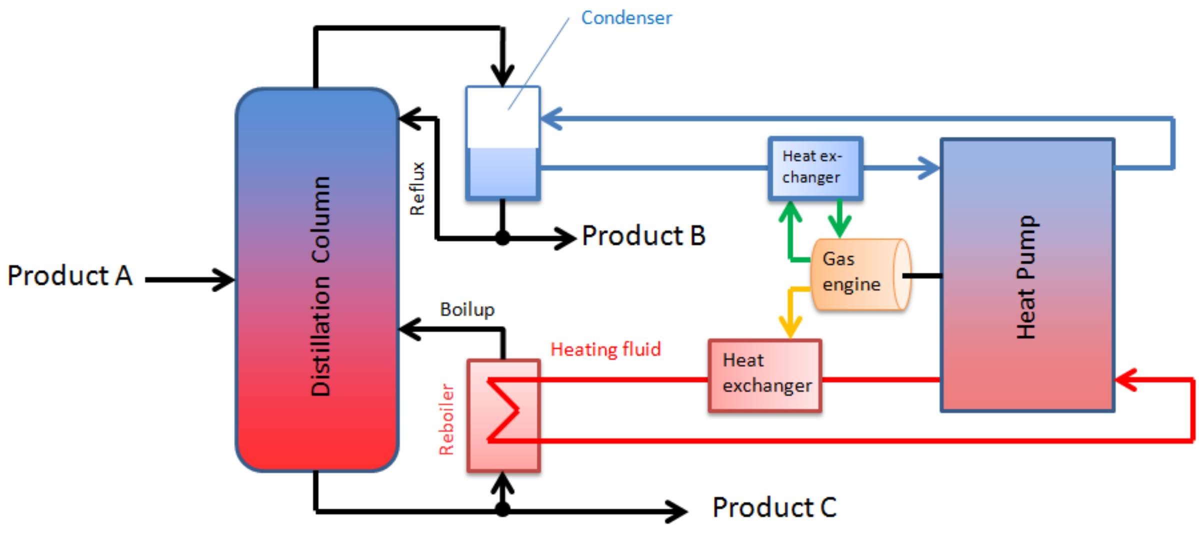

Figure 9 - Distillation column (with gas heat pump)

GDF SUEZ has developed a specific module of gas heat pump in the DYMOLA® software in order to calculate the efficiency of the setup. It was used to assess the performances of the configuration described on Figure 9.

The calculated COP (Coefficient of Performance) calculated by simulation is 1.84. As a consequence, only 500kW of natural gas is required to provide the 930kW used by the reboiler located at the bottom of the distillation column. Considering an efficiency of the steam boiler of about 85%, the natural gas consumption in the boiler is currently 1100kW. **Thus the energy savings generated by a gas heat pump is a reduction of the energy consumption up to 55%.**

Conclusions

Perspective: roadmap to develop high temperature gas heat pumps

GDF SUEZ is working with partners to develop industrial gas heat pumps systems. Besides development on the fluids to reach higher temperature, specific heat exchangers are under developments to cope with fouling fluids.

To provide systems able to recover and reuse large waste heat sources, the development of the industrial heat pumps will also focus on larger power systems. In the midterm, heat pumps able to deliver more than 2 MW are expected for special industrial use. The roadmap of the future development is described in Figure 10.

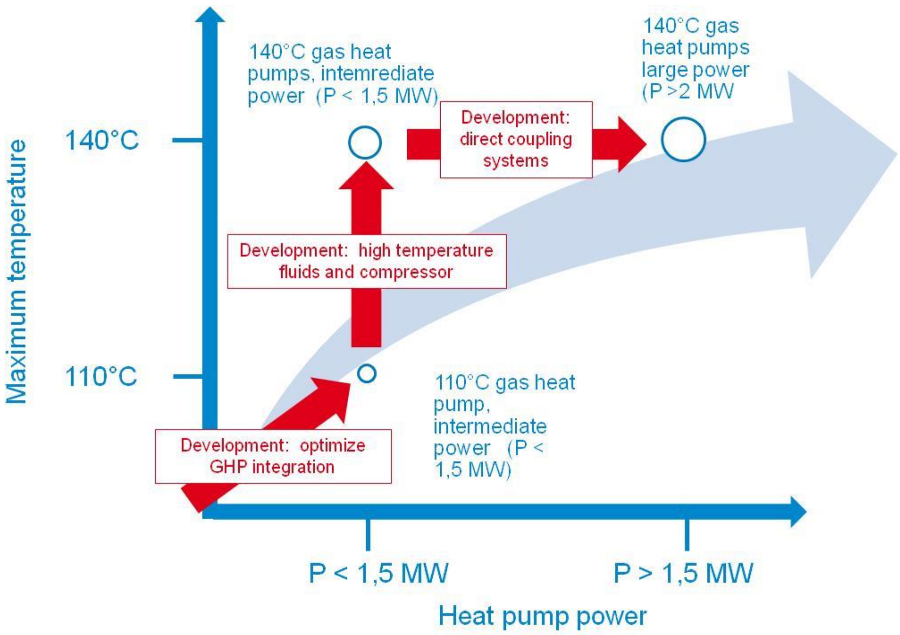

Figure 10 – High power heat pump development roadmap

To validate performances, endurance and safety of the heat pumps, it is forecast to test them on an experimental rig. Cold and hot water streams will be used to simulate various waste heats and hot sources required for various industrial processes. The experimental rig will be fully instrumented. The rig is currently under study and should be commissioned in early 2016.

Conclusions

Industrial gas heat pumps for high temperature are not currently available on the market. And yet, with the increase of the energy prices, they can be interesting for industrial end-users.

The current developments are focused on the heat recovery on the gas engine to remain competitive compared to electrical heat pumps. To support the current work, a model has been developed for integration of gas heat pumps in industrial process. Industrial tests of the pilot are also mandatory to be adopted by industrial end-users.

Further developments on the fluid are required to reach high temperature and high performances without harming the environment. To reach larger heat power, special development will be carried out to directly couple the gas engine shaft and the compressor shaft.

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