EXPERIMENTAL INVESTIGATION OF A HYDROCARBON PISTON COMPRESSOR FOR HIGH TEMPERATURE HEAT PUMPS

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1. Introduction

In industrial processes, heat demands are provided by conventional heating systems such as boilers or direct electric heating. These systems are not efficient in the use of energy resources, nor are they environmentally friendly when fossil fuels are burned in boilers or in energy production.
The availability of waste heat, which is a product in many industrial processes, provide the opportunity to be upgraded heat from low temperature to higher temperature by using a heat pump. The use of this technology will increase the efficiency of heat utilization in the industrial processes and will reduce the dependence from fossil fuel combustion.
Standard heat pumps actually available in the market cannot operate at such high thermal levels mainly because of temperature limits of traditional semiermetic compressors: high suction temperature reduces drastically the cooling of motor winding while the high discharge temperature reduces the lubricity of the oil with consequent damage of mechanical components of the compressor.
However, the developments of transcritical compressors for CO_2 have demonstrated that, with the adoption of suitable solution that separates the compression zone from the rest of the compressor, it is possible to operate with good reliability at similar temperature levels.
The development of a compressor that can operate with these high temperature conditions with high efficiency can make heat pumps an alternative and competitive solution to conventional heating systems and therefore reduce both the demand for power and CO_2-emissions.
This report shows the development of a prototype high temperature 20 kW heat pump, with two cascade circuits, capable to heat up water up to 115°C. The low temperature cycle is propane as the working fluid, while the high temperature cycle uses butane. Figure 1 below shows the schematic diagram of cascade heat pump.
Both compressors are semi-hermetic pistons; the compressor on the high temperature cycle has been modified for operation at high temperature. Temperature and pressure sensors and flowmeters to monitor operating parameters of both compressors; for obvious reasons, in this document only those relating to the butane compressor installed on the high temperature circuit will be reported.

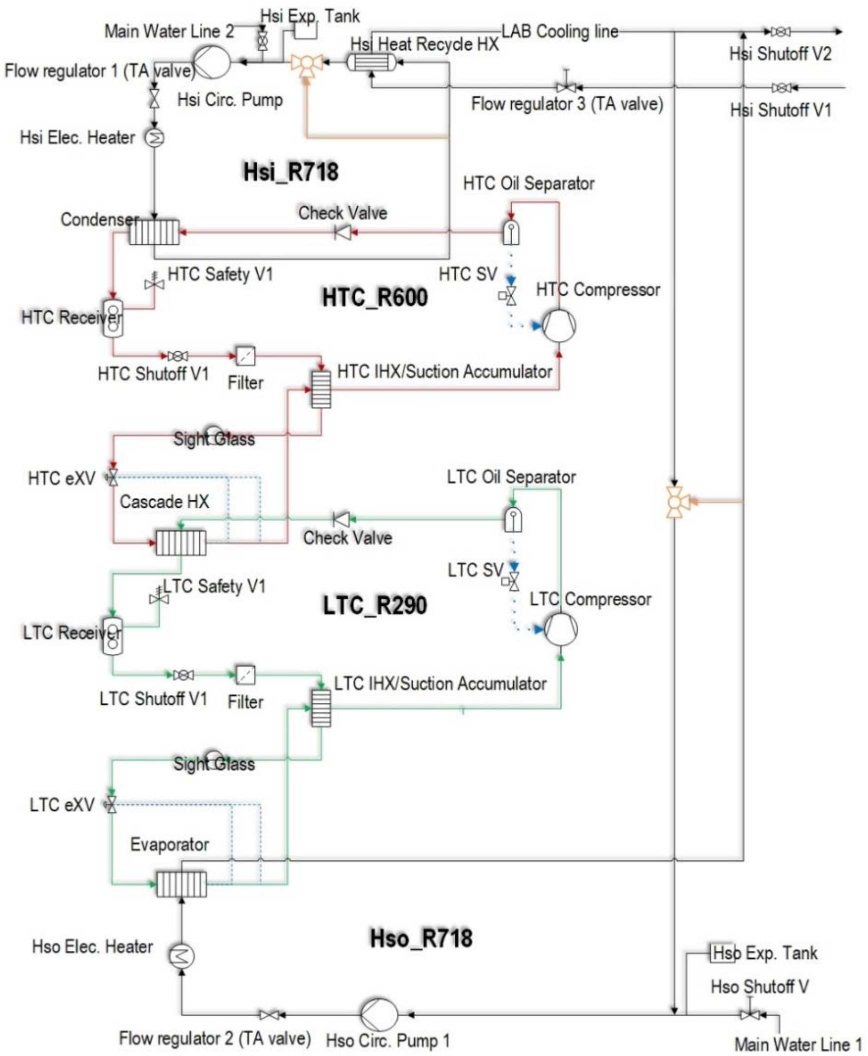

Figure 1. Schematic diagram of heat pump and testing system

2. Description of butane compressor and installed instrumentation

It is a semi-hermetic 4-cylinder piston compressor, designed for operation in an explosive atmosphere and has a displacement of 48.8 m^3/h at 50 Hz. The compressor is equipped with an external exhaust manifold to operate at the high temperatures expected. The electric motor is oversized compared to the required power and has an alarm threshold set at 140°C to be able to work at the expected high suction temperatures. The compressor is driven by an inverter to modulate the frequency between 30 and 50Hz. This will also allow better compressor flexibility for different test conditions. The compressor has a discharge temperature protection at 160°C. A high pressure switch set at 28.6 bar is installed on the discharge line for safety.

The lubrication of the compressor is recirculated towards the compressor by an oil separator. A timed valve controls the lubrication flow rate. A lubricant pickup point is installed for lubricant sampling and to assess the condition of the mechanical parts.

Temperature sensors are connected to: the compressor discharge head, the delivery pipe (about 30 cm from the head), the head on the suction side downstream of the heat exchange with the electric motor, the suction pipe 10 cm from the compressor and the lubrication chamber. The temperature of the motor windings are monitored with 6 internal thermocouples. Both suction and discharge lines are insulated with 30 mm

mineral wool insulation. The pressure sensors are connected to both suction and discharge heads. A Coriolis mass flow meter is installed in the cycle before the expansion valve and after the high pressure receiver. All sensors are connected to a data logger for data processing.
The distribution of pressure and temperature sensors for the compressor is shown in Figure 2.

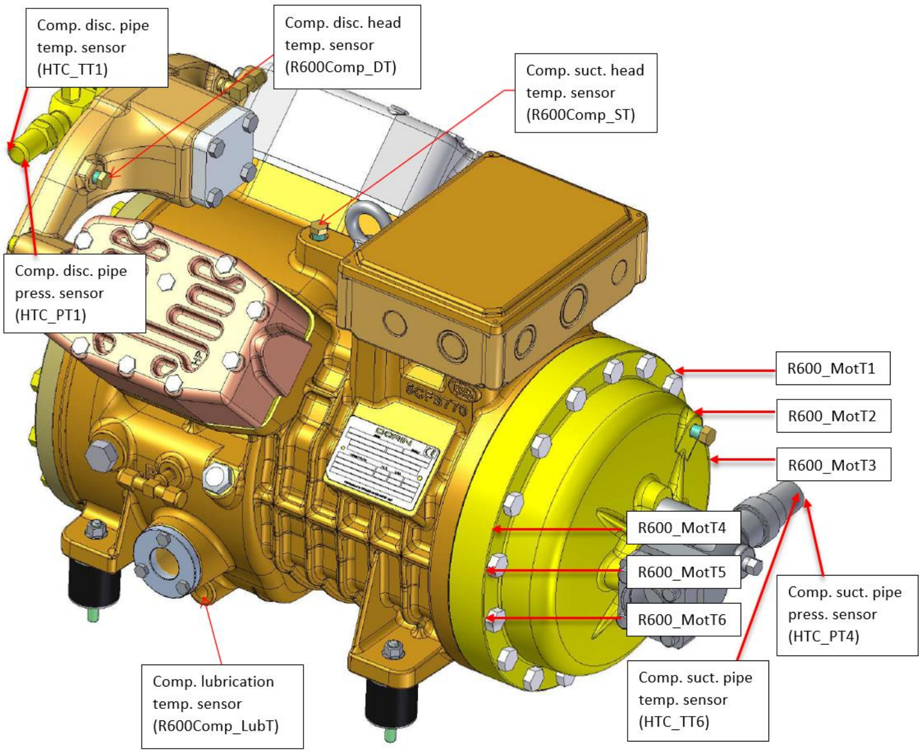

Figure 2. Pressure and temperature sensors installed on compressor

The type of sensors, the range and the accuracy of the various sensors are presented in Table 1. The electric power absorbed by the compressor is read directly by the frequency converter.

Sensor type	Model	Sensors no.	Accuracy	Range
Temperature sensor	Termocouple type K	5	+/- 2,2K	
	Termocouple type J	6	+/- 2,2K	
Pressure sensors		4	+/- 0,2% FS	0 -30 bar
Mass flow meter	Coriolis	1	+/- 0,2%	30 – 3000 kg/h

Table 1. Instrumentation installed on butane compressor

3. Results of the test

3.1 Operating temperatures

If the suction temperature is contained within 80°C, the discharge temperature is almost always kept within 140°C. These values are the maximum values foreseen by the compressor design. Only with very high overheating, the temperature exceeds 140°C. The average difference between tube and head is around 8K on the suction side and represents the heat transferred by the motor to cool the windings.

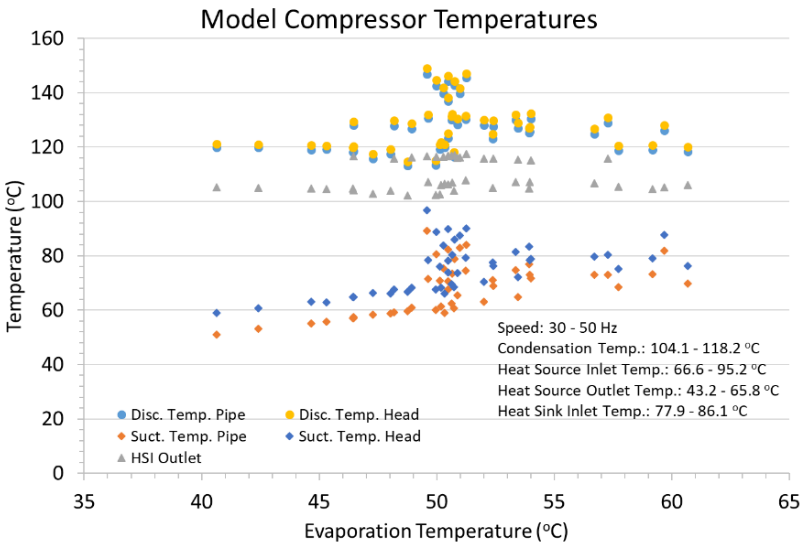

Figure 3. Suction and discharge temperature in function of evaporating temperature

3.2 Oil temperature.

The temperature is measured inside the oil pick-up screw from the crankcase. The temperature increases with increasing suction temperature and is kept below 100°C with contained superheat. Refrigerant suction flow cools the entire compressor and consequently also the oil. Values above 100°C are those related to operating points with high superheat at suction.

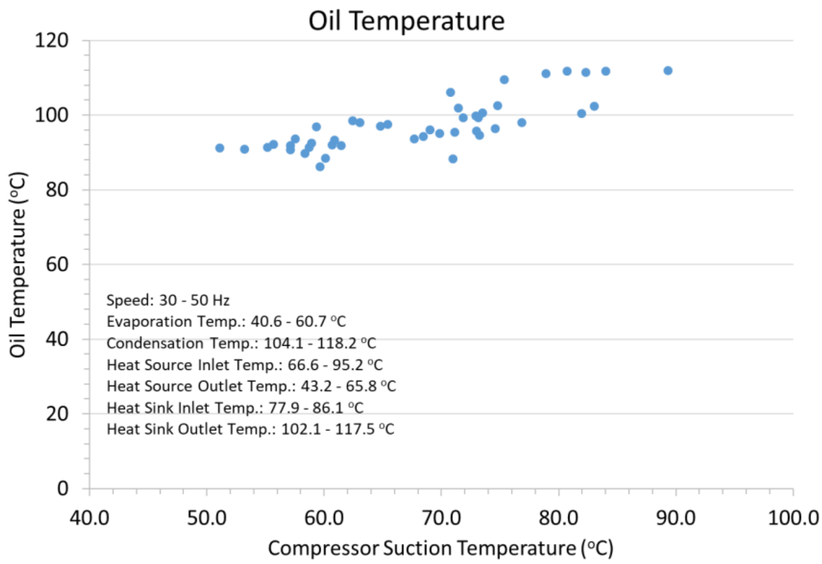

Figure 4. Oil temperature in function of suction temperature

3.3 Volumetric efficiency.

The volumetric efficiency is defined as the ratio between the volumetric flow rate of the compressor and the theoretical displaced volume. The volume flow rate is calculated as the ratio between the mass flow rate, measured with the flow meter, and the density at suction. The measured value varies between 0.87 and 0.76 depending on the compression ratio.

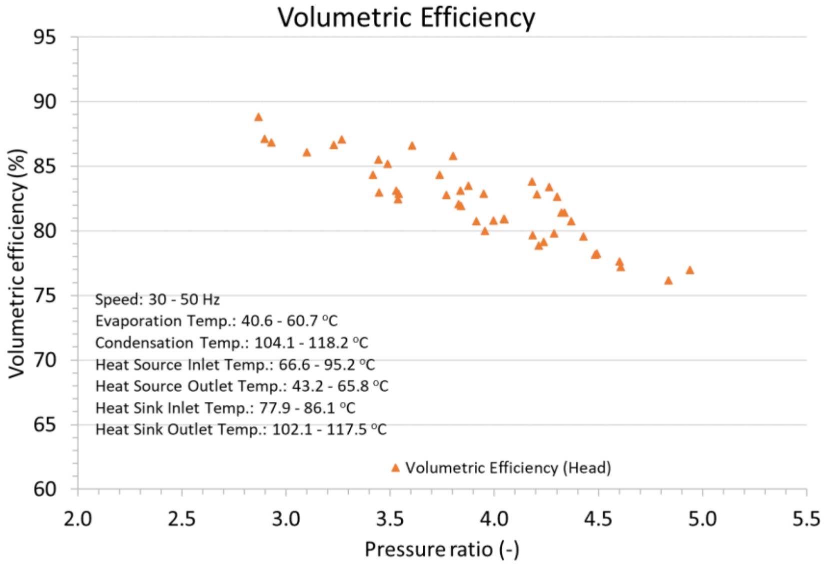

Figure 5. Volumetric efficiency in function of pressure ratio

3.4 Energy efficiency.

The overall compression efficiency is the measure of the efficiency of the compressor when all the losses (mechanical, electrical, friction, heat exchange, etc.) are considered. It is defined as the product between the mass flow rate and the isentropic enthalpy difference of the working fluid between suction and discharge, divided by the electric power absorbed by the motor. The efficiency is calculated both with the values measured on the head and on the pipes with average values of 74% and 71%, respectively.

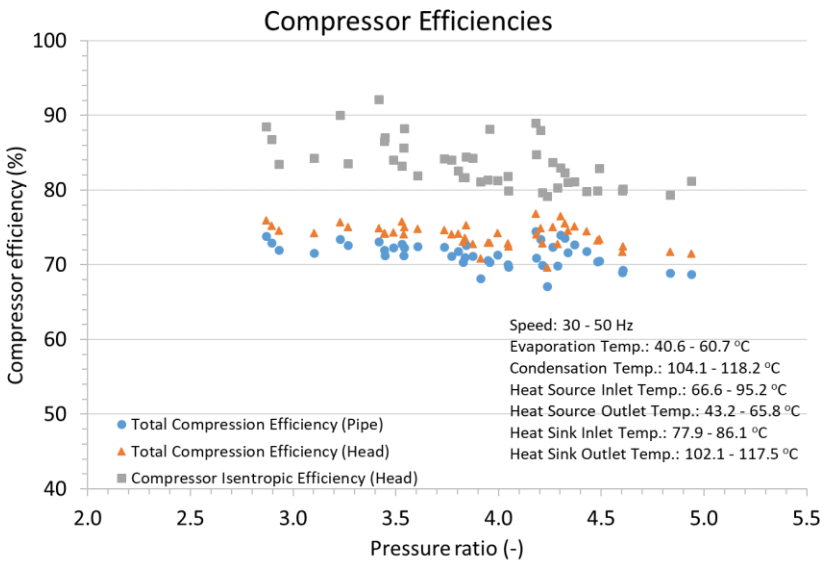

Figure 6. Energy efficiency in function of pressure ratio

4. Conclusions

This paper presents the results of an experimental campaign conducted on a prototype compressor in a special version for high temperature heat pumps. The compressor, working with butane, is installed on the high pressure circuit of a cascade cycle of a high temperature heat pump, with a thermal power of 20 kW. The compressor prototype, operated by inverter to allow variable speed operation, is instrumented with 11 temperature and 2 pressure sensors to carefully record the operating parameters and the thermal level. A mass flowmeter is also installed to calculate power and efficiency values.

The measurements made on all the operating points tested indicate an average overall compression yield of 71%. With an outlet temperature of the heated fluid of 115°C, the discharge temperature of the compressor is on average 127°C. The discharge temperature can exceed 140° C when the suction steam is excessively overheated and the suction temperature exceeds 80°C; there is no advantage to working under these conditions. The delivery pressure values remain within 22 bar and the compression ratio is always less than 5. The volumetric efficiency value varies from 75% to 85% depending on the compression ratio.

After about 250 hours of operation, the prototype compressor was inspected; despite the high thermal level all the components are in good condition without significant wear. An oil sample, taken from the compressor and analyzed in the laboratory, does not indicate significant changes in viscosity or the presence of metals.

Further experimental testings are planned with an extension of the outlet temperature of the fluid heated up to 125°C to evaluate the resistance of the prototype compressor to such severe conditions and to evaluate the performance of the lubricant in terms of viscosity and thermal stability.

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