



12<sup>th</sup> IEA Heat Pump Conference 2017



## Test results R600 pilot heat pump

Wemmers A.K., Haasteren A.W.M.B. van, Kremers P. Kamp J van der\*

ECN, Westerduinweg 3, 1755 LE Petten  
IBK koudetechniek Boogschutterstraat 1A, 7324 AE Apeldoorn  
Bronswerk Heat Transfer Stationsweg 223862 CG Nijkerk  
SmurfitKappa PPT, Groeneweg 10, 6041 AX Roermond, the Netherlands

---

### Abstract

A pilot scale compression heat pump using butane as refrigerant with a power output of 160 kW was designed, build and integrated with the paper production process on site at the SmurfitKappa Roermond mill. The project was executed to determine if it is possible to build an industrial heat pump able to produce low pressure steam from existing components and to verify the performance.

A 160 kW pilot scale heat pump able to deliver low pressure steam (1 barg) from 60°C waste heat was demonstrated at the SmurfitKappa Roermond mill. The successful demonstration confirmed that it is possible to build such a heat pump based on commercially available components.

Higher steam pressures, up to 2.4 barg, were demonstrated. It is concluded that the heat pump can operate under the maximum designed steam pressures with COP's according to the design calculations.

© 2017 Stichting HPC 2017.

Selection and/or peer-review under responsibility of the organizers of the 12th IEA Heat Pump Conference 2017.

Heat pump; butane; steam production; paper mill

---

### 1. Introduction

Steam is the most common energy carrier in industry for temperatures up to 200 °C. In Europe an estimated total of 2100 PJ steam per annum is used in refineries, chemical industry, food processing and paper industry. To give an idea of the value: 2100 PJ of steam costs approximately 18 billion euros to generate, based on the value of natural gas (28 €/MWh). At the same time recoverable waste heat is available in abundance at low temperatures. The use of heat pumps to recover and upgrade that low temperature waste heat to process steam would greatly enhance the energy efficiency of industrial processes.

The reason why heat pumps are not widely applied are both technical and economical. Due to the fact that in the past electricity was far more expensive compared to natural gas, the steam boiler and cogeneration have long been the work horses for steam generation. Since there was no market demand for electrically driven industrial heat pumps no technology was developed. However, since the turn of the century the prices for electricity have been going steadily down while the price of natural gas remained more or less the same. As a result the application of electrically driven heat pumps starts to make sense from an economic point of view, sparking an interest from process owners. Commercially available heat pumps are only able to generate process heat up to approximately 90 °C, thus seriously limiting the application of heat pumps in industry.

---

For these reasons, a new heat pump was designed based on a refrigerant (Butane, R-600) able to deliver steam of at least 2 bara (120 °C) from waste heat of 60 °C. The R-600 heat pump is developed from components (compressor, heat exchangers, controls, etc.) that are available in the market to ensure quick market introduction. This report contains the measurement results of the performance tests on an experimental R-600 heat pump. The heat pump was tested on site at the Smurfit Kappa Roermond mill. Apart from size, the experimental heat pump is identical to a full scale system (over 1.5 MW process heat) which makes the results from the tests directly applicable to full scale heat pumps. The experiments were executed to answer the following questions:

- Is it possible to build an industrial heat pump from components available in the market which is capable of producing low pressure steam (~2 bara) from low temperature (~60°C) waste heat;
- What are the technical and safety implications of integrating the heat pump with the paper production process;
- Can the heat pump operate under a variety of conditions;
- Is the measured performance consistent with the calculated performance;

The measure by which the performance of heat pumps is determined is the Coefficient of Performance (COP). The COP is the ratio between delivered process heat over supplied electricity. The investigated heat pump delivers process heat both as steam and as hot water, therefore two COP's are established: COP<sub>steam</sub> and COP<sub>steam+hot water</sub>.

## 2 Industrial heat pump system

An industrial heat pump system contains the heat pump itself and the auxiliary systems necessary to integrate the heat pump with the industrial process.

### *The heat pump*

Figure 1 below depicts the process flow diagram of the heat pump. The cycle starts in the evaporator, where butane is evaporated at low pressure with the aid of low-temperature waste heat. The low pressure butane vapor is superheated in the suction gas super-heater to avoid liquid butane during compression. The low pressure, superheated butane vapor is then compressed to produce high pressure butane vapor. The high pressure, high temperature butane vapor is condensed in the evaporator/condenser to generate low pressure steam. The sensible heat in the condensate in the butane liquid leaving the evaporator/condenser is then cooled in order to heat process water. In this way, more heat is extracted from the heat pump without the need to supply more work to the compressor. After all, for the compressor does not matter whether the low pressure vapor is generated by flashing in the expansion device or by evaporation in the butane evaporator. The final step in the cycle is the pressure drop of butane in the expansion device.

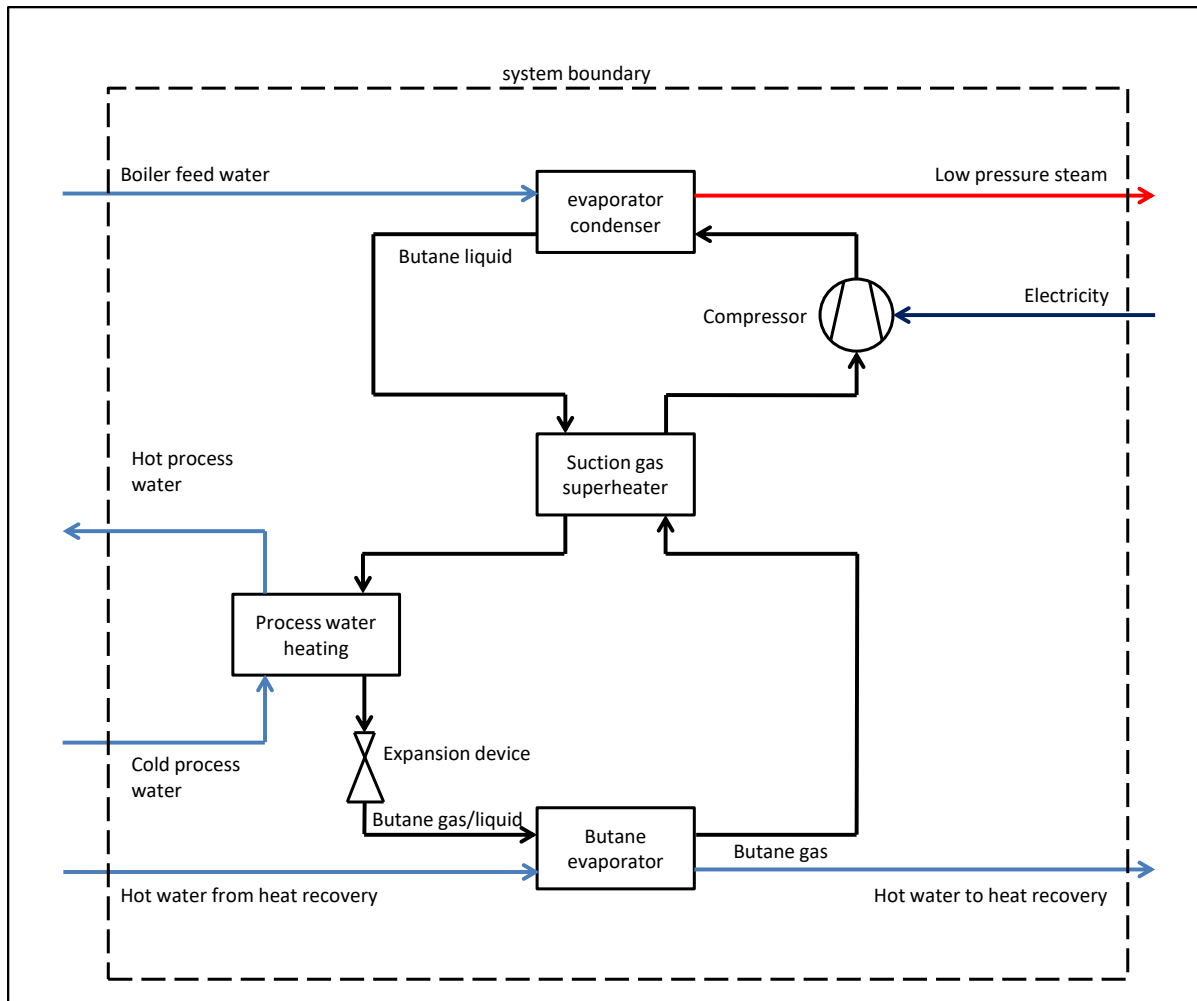


Figure 1: Evaluated heat pump system.

### **Auxiliary systems**

The auxiliary systems contain at least the following components:

- The heat recovery system which recovers low temperature from the process;
- The connections with the steam, condensate and the process water systems of the process;
- The electrical connection;
- Integration with the process control system, including the control software.

The R600 pilot heat pump in the CATCH-IT project is used to produce low pressure steam from boiler feed water and hot process water from fresh but already preheated water. The source heat is recovered from moist exhaust air from the paper machine drying section.

### **2.1 Design calculations**

To calculate a COP input parameters are needed. These input parameters are categorized in three groups: Environmental and safety requirements, end-user requirements and engineering choices.

#### **Environmental and safety requirements**

To acquire a licence to operate the heat pump it has to meet the requirements regarding environmental and safety requirements set by the government. This applies in particular to the requirements with respect to pressure devices (PED) and combustible substances (ATEX).

#### **End-user requirements**

The end-user requirements are of a set of external conditions under which the heat pump must operate:

- Delivered steam pressure and capacity;
- Delivered hot process water temperature and capacity;
- The temperature(s), characteristics (sensible heat, (partly) latent heat) and availability of the source heat.

The end-user requirements for the R-600 pilot heat pump:

- Steam pressures to be delivered at 0.5 barg up to 2.4 barg. Design capacity is approximately 150 kW and is determined by the size of the smallest available compressor. The exact capacity is depending on the operating conditions;
- Hot process water at 70 °C (maximum possible 100 °C), the capacity is the maximum possible capacity given the heat pump configuration;
- The source heat is waste heat recovered from the exhaust of the paper machine hood. The source heat is transported in a water/glycol system, the  $\Delta T_{\text{water/glycol}} = 5 \text{ K}$ , the water/glycol approach temperature varies from 60 °C up to 75 °C. The source heat is always available when there is a demand for process heat.

### **Engineering choices**

The engineering choices concern the set of internal parameters which influence the COP, the capacities and the CAPEX of the heat pump:

- Temperature differences ( $\Delta T$ 's) over heat exchangers;
- Compressor type with resulting efficiencies;
- Electric motor and controls;
- Suction gas superheating;
- Condensate sub-cooling.

### **Temperature difference**

For ease of calculation the average temperature difference instead of the more accurate logarithmic temperature difference over the heat exchangers is used:

$$\Delta T_{av} = \frac{\Delta T_{\max} + \Delta T_{\min}}{2} \quad (1)$$

where:

$\Delta T_{\max}$  is the maximum temperature difference between the streams and  $\Delta T_{\min}$  is the minimum temperature difference between the streams. In the engineering calculations an average temperature difference of 5 K has been used.

### **Compressor efficiency**

The compressor efficiency depends on the type and design of the compressor. Three categories of efficiency losses are to be considered:

- Fluid flow and mechanical friction resulting in a higher compressed gas temperature compared to isentropic compression, e.g. pressure losses over valves, leakage past the piston or lobes, etc.;
- Fluid flow and mechanical friction dissipated via the lubricating oil, cooling of the compressor casing, etcetera;
- Non adiabatic compression caused by excessive oil cooling, excessive cooling of the compressor casing, cooling of the compressed gas either via unintended heat exchange between suction gas and compressed gas or via active cooling of the compressed gas.

In the engineering calculations adiabatic compression is assumed. Furthermore the heat loss via oil is assumed to be small (<5% of the compressor work). Based on these assumptions the performance of the compressor can be calculated using an isentropic efficiency of 0.85.

### **Electric motor and controls**

The efficiency of the motor and the controls is taken at 0.95.

Suction gas superheating

The amount of suction gas superheating influences the COP's and the capacity of the heat pump. An increase in suction gas superheating results in an increase of the  $COP_{\text{steam}}$ , a decrease of the  $COP_{\text{steam} + \text{hot water}}$  and a decrease of the capacity. The suction gas superheating varies depending on the operating conditions. The set point of the suction gas superheating is given by the desired 5 K superheating of the compressed gas temperature.

**Condensate sub-cooling**

The amount of condensate sub-cooling influences the amount of heat transferred to the hot process water flow. The temperature before the expansion device is taken at 75 °C.

**2.2 Results of the design calculations**

The performance of the pilot heat pump for five different steam pressures is given in table 2.1 below.

Table 1: Calculated performance of the pilot heat pump.

measurement date	steam pressure [barg]	Calculated performance	
		$COP_{\text{steam}}$ [-]	$COP_{\text{steam} + \text{hot water}}$ [-]
mrt '15	0,5	3,7	5,1
okt '15	0,8	3,3	4,9
okt '15	1,4	2,7	4,5
okt '15	2,0	2,2	4,3
okt '15	2,4	2,0	4,2

Tevap 54°C .. 55°C

Given the Carnot efficiency (temperature of the heat delivered divided by temperature lift) it is expected that the COP reduces when the temperature lift increases. Visible from table 1 is that  $COP_{\text{steam}}$  decreases faster than the  $COP_{\text{steam} + \text{hot water}}$ . This is best explained using the Temperature Entropy diagram shown in Fig. 2.

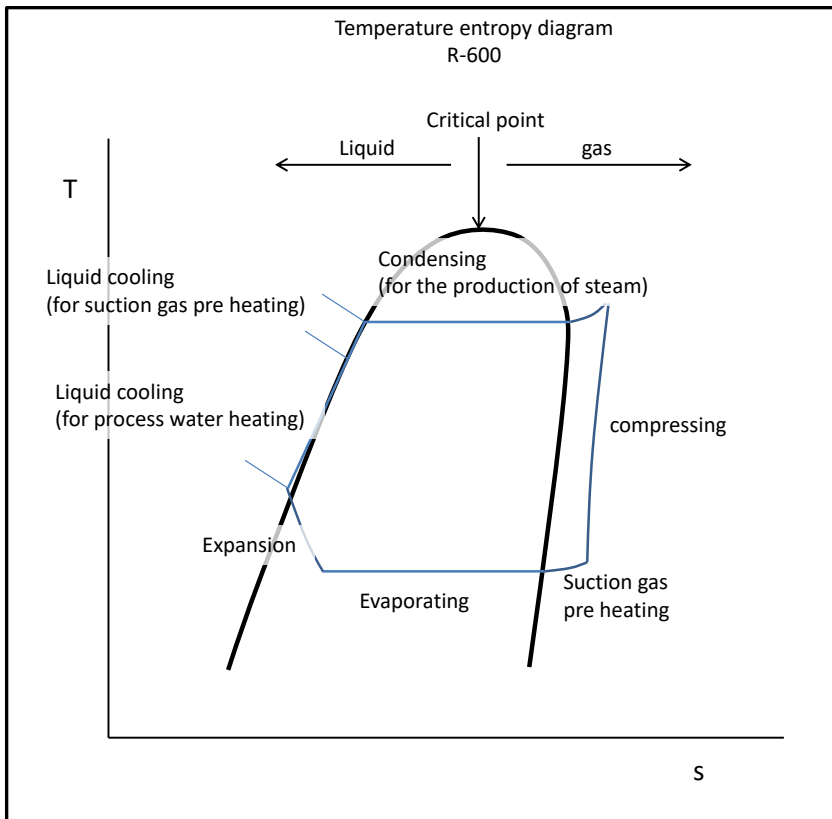


Figure 2: Temperature Entropy diagram for butane.

Increasing the condensation temperature means that the heat of evaporation becomes less. Finally, when the condensation temperature is at the temperature of the Critical point (150.8 °C, for butane) there is no heat of evaporation left, hence no steam is produced. The sensible heat of the butane liquid leaving the condenser increases with increasing condensation temperature. As a result the amount of heat available for heating process water increases hence the COP for steam and hot water remains higher.

### 3 Measurement program

Although a complete heat pump system is necessary to operate the heat pump, the performance evaluation focusses on the heat pump itself. The system boundary for the performance evaluation of the heat pump and the measuring points used to collect the necessary data are depicted in the schematic of Figure 3. To be able to identify the equipment used for data collection the TAG numbers are also given in Figure 3.1. The heat pump forms an integral part with the Paper Mill's process control system (PI system from OSIsoft) which means that all the measuring points are continuously logged on an one minute interval and stored for future reference.

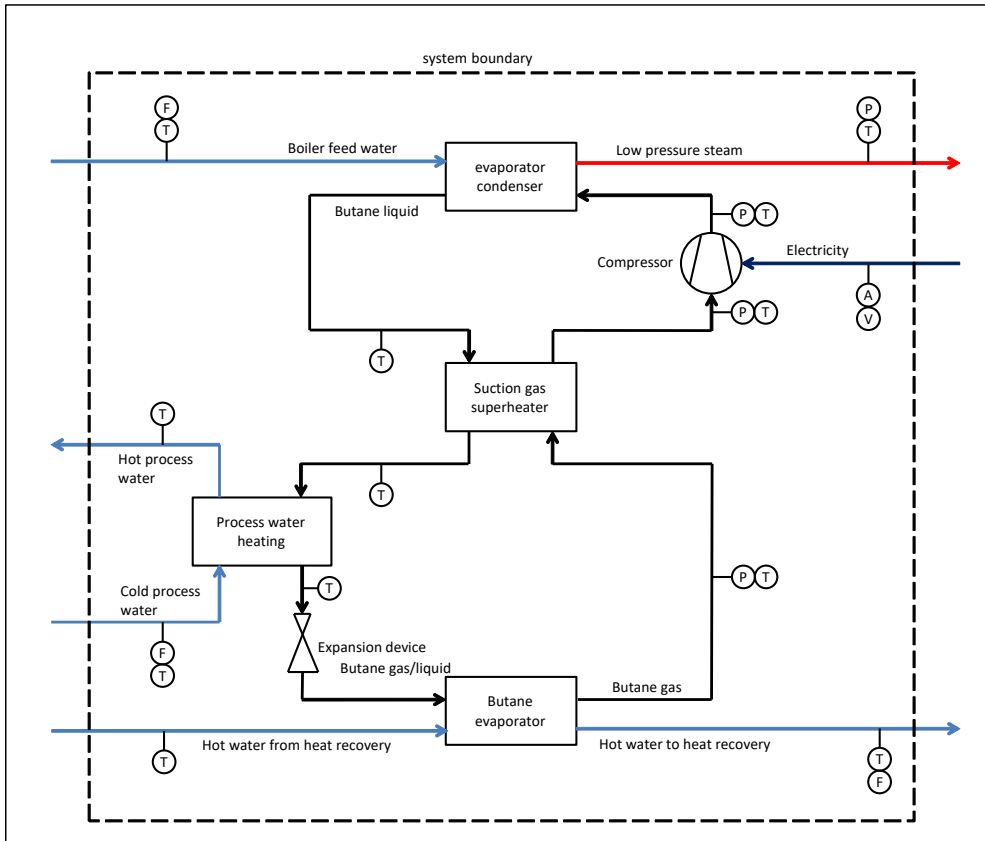


Figure 3: Evaluated heat pump system and measuring points.

**Measuring method**

For the heat pump depicted in Figure 3 an external and an internal energy balance are made for each operation condition. From these energy balances the COP's are calculated and compared to the theoretical COP's. The theoretical COP's are calculated from the design conditions and assumptions. By comparison of the measured and calculated COP's, conclusions are drawn on:

- The performance of the heat pump;
- The reliability of the design calculations.

**External energy balance**

The external energy balance consists of the heat and electricity which flow over the system boundary, depicted as the dashed line in Figure 3. The heat flows are determined by:

$$\dot{Q}_i = \dot{m}_i \times \Delta h_i \tag{2}$$

The mass flow ( $\dot{m}_i$ ) of stream  $i$  and its temperatures are measured for the boiler feed water, the hot process water and the heat recovery water. To establish the enthalpy of the produced steam, the steam pressure and temperature are also measured. The specific enthalpy ( $h$ ) is determined using the NIST Standard Reference Database 23, version 9.1 (Lemmon et al., 2013) which enables the calculation of specific enthalpies from measured temperatures and, in case of vapor, from temperatures and pressures.

The electricity used by the compressor is measured at the frequency controller of the compressor motor.

**Internal energy balance**

The internal energy balance consists of the amounts of heat and work transported by the butane inside the reverse Rankine cycle. The internal energy balance is calculated per kilogram of butane since the butane mass flow is an unknown. The temperatures and pressures of the butane are measured at the points given in Figure 3.

The specific enthalpy ( $h$ ) of the butane at each point is determined using the NIST Standard Reference Database 23, version 9.1 (Lemmon et al., 2013). To be able to compare the COP's from the internal and external energy balance the amount of compressor work is divided by the efficiency of the electric motor, the efficiency is set at 95%.

### 3.3 Comparison calculations and measurements

In table 1 below the measured performance data is compared to the calculated performance data.

Table 2: Comparison between calculated and measured performance.

measurement date	steam pressure [barg]	Calculated performance		Measured performance	
		COP <sub>steam</sub> [-]	COP <sub>steam + hot water</sub> [-]	COP <sub>steam</sub> [-]	COP <sub>steam + hot water</sub> [-]
mrt '15	0,5	3,7	5,1	3,6	5,1
okt '15	0,8	3,3	4,9	3,0	4,7
okt '15	1,4	2,7	4,5	2,6	4,6
okt '15	2,0	2,2	4,3	2,2	4,6
okt '15	2,4	2,0	4,2	1,9	4,4

Te vap 54°C .. 55°C

Comparison of the measured COP's and the calculated COP's show (small) differences. Most of the differences can be explained by differences between the conditions during testing and the conditions for the calculations. Most noticeable:

- The temperature differences over the heat exchangers are smaller in practice than the assumed 5 K in the calculations;
- The isentropic efficiency of the compressor is lower (approximately 0.8 depending on specific operating condition) than the assumed 0.85;
- In most cases the COP<sub>steam</sub> internal is somewhat lower than the theoretical COP<sub>steam</sub> at the same time the COP<sub>steam + hot water</sub> internal is somewhat higher than the theoretical COP<sub>steam + hot water</sub>. This suggests that heat is transported from the compressor to the process water heater via the oil and cylinder head cooling circuit.

### 4 Conclusions

A 160 kW pilot scale heat pump able to deliver low pressure steam from 60°C waste heat was demonstrated at the SmurfitKappa Roermond mill. The successful demonstration confirmed that it is possible to build such a heat pump based on commercially available components.

The heat pump was tested at different operating conditions. The critical operating conditions from a technical point of view are higher steam pressures. Higher steam pressures are associated with higher pressures and temperatures which impose additional thermal and mechanical strains to the heat pump. Higher steam pressures, up to 2.4 barg, were demonstrated. Operating conditions which impose no additional strain to the heat pump and which were solely intended to verify expected variations in capacity and COP's were not demonstrated. It is concluded that the heat pump can operate under the maximum designed steam pressures.

## **References**

1. Lemmon, E. W., Huber, M. L., and McLinden, M. O. (2013). NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP, Version 9.1, National Institute of Standards and Technology, Standard Reference Data Program, Gaithersburg.