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ABSTRACT

Many opportunities for heat pumping technologies exist for recovering the waste heat generated by industrial processes. By using heat pump systems in the right way, the use of primary energy and CO2 emissions as well as energy costs can be reduced. A laboratory flexible industrial scale heat recovery system is designed and built to carry out experimental simulations by reproducing the operating conditions of real case applications in food industries. The heat recovery system includes process integration technologies ranging from passive recovery like simple heat exchangers to technologies upgrading the waste heat like industrial heat pumps. The integrated heat pump is an electrically-driven vapor compression closed-cycle type, which can operate in a single-stage or in a 2-stage configuration and has a variable speed screw compressor. Several typical scenarios of food industry processes for low-temperature heat recovery (heat sources between 30°C and 50°C) and heat upgrading are experimentally simulated showing the overall energy savings and the environmental benefits of introducing heat pumps in this kind of industrial applications. The optimal configuration of the heat recovery system is evaluated for each scenario.

Key words: Heat recovery, industrial processes, heat pumps, experimental simulation.

1. INTRODUCTION

Industrial processes generate waste heat and at different temperature levels. An energy efficient and cost effective solution is to reduce industrial processes fossil fuel consumption by recovering process waste heat and using it to meet heating requirements. Additionally, this constitutes a considerable benefit to the environment and its resources. While heat exchangers can transfer this wasted heat to lower temperature applications, heat pump technologies have the possibility to upgrade this heat and make it useful in higher temperature applications. The international study (IEA HPP, 1995) has shown great potential and major opportunities for industrial heat pumps to recover process waste heat especially in the food industries. However, relatively few heat pumps are currently installed in industry. The main barriers are lack of experiences and few reference demonstrators to promote this technology. In this work, experimental simulations reproducing real case operating conditions from different applications in food industries are carried out on an industrial scale heat recovery system. The system includes the process integration technologies: a plate heat exchanger (HX) and an electrically-driven vapor compression heat pump (HP). The performance of the heat recovery heat pump system is evaluated for several typical scenarios.
2. HEAT SOURCES AND HEAT SINKS FOR HEAT PUMPS IN FOOD INDUSTRIES

A recent study in France (Dupont and Sapora, 2009) showed that food industries are the largest consumers of low-temperature industrial heat. Food industries include beverages, meat products, dairies, cheese and sugar productions, and general food products. Figure 1 presents the distribution of heat needs up to 80°C between the French industrial sectors and indicates that food industries require around 45% of the total heat demand. A recent market analysis for large scale industrial heat pumps in Germany (Lambauer et al., 2008) also showed similar results.

Concerning the level of temperatures for possible usages, Figure 2 illustrates the distribution of heat per usage up to 80°C and 100°C of process temperature level between the industrial sectors in France. It is noticeable that liquid and gas heating is the predominant need below 100°C.

### 2.1 Heat sources

The nature of food processing offers many opportunities for heat pumps in food industries. The plant waste heat is the heat source of the heat pump. The common waste heat streams in food industries are effluent, sewage, moisture, and condenser heat from refrigeration plants. The average temperature level of the waste heat varies typically between 30°C and 50°C. Table 1 shows some examples of waste heat type with the corresponding temperature level (EDF R&D, 2010). The flow of the waste stream and the temperature level will determine the amount of available heat source for the heat pump.

![Figure 1: Heat needs distribution up to 80°C per industrial sector in France.](image1)

![Figure 2: Distribution of heat needs per usage in French industries up to 80°C and 100°C.](image2)

<table>
<thead>
<tr>
<th>Waste heat</th>
<th>T [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air compressor cooling</td>
<td>25 - 50</td>
</tr>
<tr>
<td>Refrigeration heat rejection</td>
<td>30 - 45</td>
</tr>
<tr>
<td>Effluent / Cleaning systems</td>
<td>30 - 50</td>
</tr>
<tr>
<td>Re-cooling water</td>
<td>25 - 35</td>
</tr>
</tbody>
</table>

Table 1: Examples of some waste heat temperature levels from food industrial processes.
2.2 Heat sinks
Food industries need warm and hot process water in the 40°C to 90°C temperature range. They also require to heat process streams to a temperature determined by the process. Besides they have often a significant hot water demand in the same temperature range for washing and cleaning purposes. Table 2 gives examples of some processes from different branches of food industries with the associated process temperature (EDF R&D, 2010). The temperature level of the process depends also on the product variety and on the manufacturer.

<table>
<thead>
<tr>
<th>Branch / Activity</th>
<th>Process</th>
<th>T [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Juice manufacturing</td>
<td>Pasteurization</td>
<td>75 - 95</td>
</tr>
<tr>
<td>Dairy products</td>
<td>Pasteurization</td>
<td>75 - 95</td>
</tr>
<tr>
<td>Cheese processing</td>
<td>Pasteurization</td>
<td>63 - 75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>67</td>
</tr>
<tr>
<td>Brewery</td>
<td>Pasteurization</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mash</td>
<td>80</td>
</tr>
<tr>
<td>Slaughter houses</td>
<td>Warm water</td>
<td>40 - 60</td>
</tr>
<tr>
<td>Meat processing</td>
<td>Hot water</td>
<td>80</td>
</tr>
<tr>
<td>General food products</td>
<td>Cleaning / washing water</td>
<td>50 - 90</td>
</tr>
</tbody>
</table>

2.3 Process integration of heat pumps
As shown above, a number of opportunities exist for heat pumping in food industries and in any industry having the same temperature range of heat sources and heat sinks. However, the integration of heat pumps in industrial processes suffers of lack of consistent methodologies for assessing the optimal integration especially when considering the overall industrial process. Therefore, an important tool for process integration is the pinch analysis, a tool that uses vector analysis to evaluate process hot and cold streams and to identify possibilities for heat recovery including heat exchangers and heat pumps (Linnhoff and Townsend, 1983). In our experimental work, only two streams are considered for each scenario, so the principle of the pinch analysis is simplified for two streams and illustrated in Figure 3. Accordingly the heat recovery heat pump system operates following one of the two modes:
If \( T_{\text{cold, in}} \) is lower than \( T_{\text{waste}} \), then the HX is activated before activating the HP. On the contrary, if \( T_{\text{cold, in}} \) is higher than \( T_{\text{waste}} \), then only the HP is activated.

The Coefficient of performance (COP) of the heat pump and of the system are evaluated using Equation (1) and Equation (2) respectively, where \( W_{\text{comp}} \) is the compressor input power of the HP (circulation pumps input power is considered out of the generation system boundaries).

\[
COP_{\text{HP}} = \frac{Q_{\text{HP}}}{W_{\text{comp}}} \\
COP_{\text{System}} = \frac{Q_{\text{HX}} + Q_{\text{HP}}}{W_{\text{comp}}}
\]
3. TEST BENCH DESCRIPTION

3.1 Experimental set-up
The experimental set-up is composed of three parts: two hydraulic loops and a heat recovery heat pump system. The first “high temperature” hydraulic loop includes a water tank, a variable capacity dry cooler, a controlled electric heater, and a water pump with adjustable volume flow rate. It simulates the process heat requirement. The second “low-temperature” hydraulic loop includes a water tank, a controlled electric heater, and a water pump with adjustable volume flow rate. It simulates the waste heat requirement. The heat recovery heat pump system includes the process integration technologies: a counter-current plate type heat exchanger (HX) and an electrically-driven vapor compression heat pump (HP). Figure 4 shows a schematic diagram of the experimental apparatus.

The HP technology was not designed; it was imposed by the commercial availability. The only conditions for the heat pump manufacturer were:
- a 700-kW water-to-water electrically-driven vapor compression heat pump with capacity modulation
- A non-toxic, non-flammable, environmentally safe working fluid for high-temperature applications
- An output hot water temperature as high as possible.

The manufacturer choices gave the following heat pump technology:
- A double screw oil injected compressor with variable volume ratio and variable speed electric motor (including oil separation and oil cooling).
- A shell-and-tube condenser with integrated sub-cooler.
- A dry expansion U-type shell-and-tube evaporator
- An electronic expansion valve
- HFC-134a as working fluid

![Figure 4: Scheme of the experimental set-up.](image-url)
3.2 Transducers and data acquisition systems
Several sensors are installed on different spots of the experimental system (cf. Figure 4):

- Temperature transducers PT100 with an accuracy of ±0.5K in the operating range of 0 to 100°C at the inlet and outlet of each component in the hydraulic loops.
- An electromagnetic flow-meter on each hydraulic loop, with an accuracy of ±0.25% in the operating range of the experimental conditions.
- A wattmeter to measure the compressor input power with an accuracy of ± 0.5% in the operating range 0 to 160 kW.

All sensor measurements were collected at steady state conditions using a dedicated PC via convenient data acquisition software.

4. RESULTS AND DISCUSSION

4.1 Experimental results
Experimental tests were carried out at EDF R&D - EPI Department at the Renardières laboratory. With HFC-134a as a working fluid, the maximum possible hot water temperature was 75°C due to the high pressure limit (2.5 MPa was the maximal allowed high pressure according to the manufacturer). Accordingly, different process temperatures below 75°C were experimentally simulated with nearly a constant heat capacity of 500 kW for different waste heat scenarios. Figure 5 shows the HP performance in several process scenarios for heat source temperature levels varying between 30°C and 50°C, with a fixed flow rate value of 46 m³/h. Figure 6 illustrates the sensitivity of the HP COP to the waste heat volume flow rate (VFR) variation for a fixed process temperature of 75°C. We can conclude that the HP COP is affected heavily by the VFR variation (maximum observed decrease about 23%) as the HP evaporator temperature must decrease when the VFR decreases to recover the same amount of heat.

![Figure 5](#)

![Figure 6](#)

Figure 5: Heat pump COP for different process scenarios at constant heat capacity of 500 kW and constant waste heat VFR of 46 m³/h.

Figure 6: Heat pump COP for different waste heat scenarios delivering a heat capacity of 500 kW at 75°C process temperature.

Table 3 gives the results when a complementary heat recovery with a heat exchanger installed upstream the HP was possible, typically when the heated fluid has a large temperature glide (example: wash water generation from city water). Two operating modes are compared for two desired temperature levels (55°C and 65°C) with or without passive HX recovery. The results are evaluated in terms of HP COP Equation (1) and System COP Equation (2) for each mode and scenario. Although the HP COP decreases when HX recovery is activated and increases when the HX is by-passed, the system COP is better when both the HX and the HP are activated. Indeed, less compressor input power is observed when the HX recovers the first part of the waste heat, which increases the overall performance of the system for the same supplied heat capacity.
Table 3: HP COP and System COP for waste heat VFR of 46 m³/h and wash water VFR of 10.8 m³/h.

<table>
<thead>
<tr>
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<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>HXHP55</td>
<td>34</td>
<td>15</td>
<td>55</td>
<td>206</td>
<td>295</td>
<td>501</td>
<td>4.8</td>
<td>8.2</td>
</tr>
<tr>
<td>HP55</td>
<td>34</td>
<td>15</td>
<td>55</td>
<td>0</td>
<td>500</td>
<td>500</td>
<td>5.3</td>
<td>5.3</td>
</tr>
<tr>
<td>HXHP65</td>
<td>34</td>
<td>15</td>
<td>65</td>
<td>206</td>
<td>420</td>
<td>626</td>
<td>4.4</td>
<td>6</td>
</tr>
<tr>
<td>HP65</td>
<td>34</td>
<td>15</td>
<td>65</td>
<td>0</td>
<td>626</td>
<td>626</td>
<td>4.4</td>
<td>4.4</td>
</tr>
</tbody>
</table>

4.2 Discussion for enhancement of HP and system performance

A solution is suggested to enhance the HP COP and hence the system COP especially for scenarios with low waste heat VFR. It is observed above that for small waste VFR a large water temperature drop occurs in the evaporator degrading the HP COP with the tested pure working fluid HFC-134a. Consequently, a new low GWP non-azeotropic ternary blend (WF.7), developed and experimentally tested by Nehme (2009) for domestic hot water generation, is suggested. By keeping the same measured values of temperature approaches in the condenser and in the evaporator, the measured value of the compressor isentropic efficiency and of the electric motor efficiency, the thermodynamic cycle of this blend is theoretically simulated using RefProp 8 (Lemmon et al., 2008) and compared to the measured HFC-134a cycle in the same scenarios.

The two thermodynamic cycles in T-s diagrams are presented in Figure 7 for the same operating conditions. Temperature glides occur during the phase changes of WF.7 causing less irreversibilities in the condenser and the evaporator, and improving the HP COP, at least theoretically.

Figure 7: Comparison of thermodynamic cycles in T-s diagrams, for HFC-134a (on the left) and WF.7 (on the right), working in the same scenario of 75°C process temperature and a waste VFR of 46 m³/h at 50°C.

Figure 8 presents a first comparison between the measured and the calculated HP performances, using HFC-134a and WF.7 respectively, for the same process and waste heat scenarios. Results show that HP performance with WF.7 is improved; maximum gain about 16%, and an average gain of 10% in comparison to the HP performance with HFC-134a.

However, these theoretical simulations should be experimentally tested to confirm these conclusions. Furthermore more attention should be paid to the current heat exchanger technologies of the test bench because counter-current flows configuration is needed to take full advantage of this non-azeotropic blend. This issue will be the subject of future investigations.
5. CONCLUSIONS

As shown in this paper, many opportunities for heat pumping technologies exist for recovering the waste heat generated by industrial processes, particularly in food industries thanks to the nature of food processing. A laboratory industrial scale heat recovery heat pump system is built to carry out experimental simulations by reproducing the operating conditions of real case applications in food industries. Heat sources between 30°C and 50°C, and process temperature levels between 60°C and 75°C are tested for a supplied heat capacity around 500 kW. HP and system COPs are measured showing generally good energy performance.

Furthermore, significant improvements are possible using non-azeotropic refrigerant blends, especially when large temperature glide heat sources are necessary for waste heat recovery. Finally, for a given industrial scenario, the working fluid and the technology should be studied to select the best efficient heat recovery heat pump.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>COP</td>
<td>Coefficient of performance</td>
<td>(kW/kW)</td>
</tr>
<tr>
<td>Q</td>
<td>Heat capacity</td>
<td>(kW)</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
<td>(°C)</td>
</tr>
<tr>
<td>VFR</td>
<td>Volume flow rate</td>
<td>(m³/h)</td>
</tr>
<tr>
<td>W</td>
<td>Mechanical power</td>
<td>(kW)</td>
</tr>
</tbody>
</table>

Subscripts:
- comp: compressor
- in: inlet
- out: outlet

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Lemmon, E.W., McLinden, M.O., Huber, M.L., 2008. NIST Standard Reference Database 23 (Ref prop), Version 8.0, National Institute of Standards and Technology, Gaithersburg, MD.