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Influence of the Refrigerant Maldistribution in the Performance of Brazed Plate Heat Exchangers Working with Propane

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ABSTRACT

Brazed plate heat exchangers (BPHEs) are used widely in heating and cooling systems, mainly for liquid-to-liquid heat transfer but also for two-phase-applications like evaporation and condensation. Using them as evaporator or condenser in a heat pump the proper performance of them strongly influences the energy efficiency of the cycle and the required amount of refrigerant. One of the most common factors affecting the performance of BPHE is the not uniform distribution of the refrigerant. This problem is especially important in the evaporator as the refrigerant enters in it in two phase flow and usually the distribution of liquid and vapor is not uniform over all the channels. This problem is very well known in the literature, and manufacturers have implemented some technical solutions like introducing distributors in the inlet port in order to minimize this effect. Nevertheless, the applied solutions usually are developed only for nominal conditions. The deviations in performance at part load conditions of the BPHE can be strong, but they are normally not known. In this contribution, an experimental analysis of the refrigerant distribution in an evaporator BPHE as a function of the inlet and outlet conditions will be presented. The BPHE has been tested and evaluated working at several inlet conditions (quality) and outlet conditions (superheat) for different temperature difference in the secondary fluid. As refrigerant propane was used, the refrigerant distribution inside the BPHE has been registered using thermography. It has been seen that: i) the flow maldistribution is present in most of the tests, ii) the quality of the refrigerant at the inlet influences the flow distribution, iii) the required superheat can have some influence, iv) the influence of the refrigerant maldistribution on evaporating temperature depends on the testing conditions resulting on a very significant degradation of the COP in some cases.

1. INTRODUCTION

The use of brazed plate heat exchangers (BPHEs) for two-phase flow boiling was increasingly investigated within the last 10-15 years with the intention of using the high compactness and efficiency. Refrigerant maldistribution has been observed in this kind of heat exchangers overall when high demands and large heat exchangers are needed. As a consequence of that, the heat transfer can be highly degraded affecting significantly to the global system performance.

Early literature on the plates arrangements on flow distribution is presented by Bassiouny and Martin (1984a) and (1984b) for one phase flow. The results observed shows that manifold diameter and number of channels have great influence in maldistribution. The influence of the shape of the plates has been also analyzed by some authors and for instance, Thonon and Mercier (1996) found that Z-type plate arrangement have more tendency to suffer maldistribution.

The quality distribution in heat exchanger manifolds were investigated by Vist and Pettersen (2004) and thermal performance can be reduced due to liquid/vapor maldistribution. From their observations, vapor is taken out in the first channels when the inlet quality was low (x=0.11) but distributes evenly in the first channels when quality increased. However, no mention about the superheat in the evaporator is made.
Mass flow, flow pattern and inlet quality are variables to consider achieving mass flow evenly distributed within the channels. For high mass flow and low inlet quality, better distribution is mentioned by many researchers Brix et al (2009), Jensen et al (2015). However, depending on the flow pattern better or less distribution is observed. Flow visualization before entering the evaporator recognized two patterns: churn and separated flow. Churn flow is recommended as liquid and vapor phase are homogeneously mixed whereas in separated flow, the different layers of vapor and liquid, according to Zou and Hrnjak (2013) are perfectly separated.

Infrared thermography has been used in order to study this phenomenon. It has the advantage of being non-intrusive and non-contacting, which makes this technic easy to apply. In the works of Bowers et al (2006) or Longo (2010) thermography was used in microchannel heat exchangers to visualize the two-phase flow region for different outlet vapor qualities and superheats of 5 and 10 K and to outline a methodology to quantify both refrigerant maldistribution and effective usage of the heat exchanger respectively. Nevertheless, thermography supply information about the surface temperature of the heat exchanger and special care must be taken in order to interpret properly the obtained results.

In this paper, a theoretical analysis about the possible influence of the maldistribution in the performance of a BPHEs is done. This analysis has been performed over a function of different operation parameters like evaporator inlet quality, evaporator superheat and water temperature difference. The analysis has been used in combination with an experimental campaign in order to evaluate the real degradation of the evaporator performance and some applications where the described factors could have an influence has been described.

2. EXPERIMENTAL SET UP

The test bench for the characterization of water to water heat pumps was used. The test bench was able to control the water mass flow through the evaporator and the condenser in such a way that it allows maintaining a constant water temperature difference at a constant inlet water temperature in both heat exchangers. In this test bench a heat pump able to control its operational subcooling and superheat has been installed. The basic schemes of the two configurations of the heat pump are shown in figure 1. Figure 1(left) shows the configuration with variable superheat and the figure 1 (right) shows the configuration with 0 superheat.

Figure 1. Configuration of the system layout for variable superheat (left) and 0K superheat (right)

Figure 3 shows a scheme of the test unit with all the instrumentation used. The green box corresponds to the BHPE evaporator. The sensor used in the test rig with their relative and absolute accuracy are summarized in table 1.

The main characteristic of it are 120 plates, a horizontal port distance and vertical port distance of 50 mm and 466 mm respectively resulting a 6 m² heat transfer area.
Figure 2. Propane Water-to-water heat pump in which the refrigerant distribution in the evaporator has been tested.

Table 1. Instrumentation used in the test rig

<table>
<thead>
<tr>
<th>Instrumentation</th>
<th>Model</th>
<th>Relative accuracy</th>
<th>Absolute accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>P 1151 Smart GP7 Rosemount</td>
<td>0.12 % of Span</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>P 1151 Smart GP8 Rosemount</td>
<td>0.15 % of Span</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>P 3051 TG3 Rosemount</td>
<td>0.14 % of Span</td>
<td>0.04</td>
</tr>
<tr>
<td>Temperature</td>
<td>RTD Class 1/10 DIN</td>
<td></td>
<td>0.06</td>
</tr>
<tr>
<td>Mass Flow</td>
<td>Coriolis SITRANS FC MASS 2100</td>
<td>0.3 % of Reading</td>
<td></td>
</tr>
<tr>
<td>Thermography Cam</td>
<td>FLIR P640</td>
<td>0.3 %</td>
<td>2°C</td>
</tr>
</tbody>
</table>

A more detailed information about the system configuration and the used instrumentation can be found in Pitarch et al. (2017).

In order to register the temperature image of the heat exchanger channels, the infrared camera FLIR P640 was used. The sensibility of the camera is of 30mK. It should be commented that although the temperature was performed over the lateral surface of the heat exchanger, and probably it will have a deviation from the real temperature of the fluid in each channel, based on the obtained results the authors consider that it could be a reasonable picture of the refrigerant distribution in the BPHE and therefore, the performed measurements represent properly the heat transfer process in the BPHE. This picture has complemented with the measurement of the evaporating temperature, the refrigerant temperature at the evaporator outlet and the water temperature at the inlet and outlet of the evaporator.

Figure 2 shows a transversal picture of the evaporator installed in the system and a frontal view with the location of the refrigerant and water inlet/outlet ports. As it can be seen in the picture, the transversal side of the evaporator was covered with a non-reflective painting in order avoid any possible dispersion derived from undesired environmental radiation reflections. Figure 2 also shows an example of a thermography results obtained from the performed experiments.
Figure 3 Picture of the BPHE under analysis, frontal view with the location of the inlet/outlet ports and example of obtained thermographies.

It should be pointed out that the image of the thermography shows a temperature maldistribution, not exactly an uneven refrigerant mass flow maldistribution. This temperature maldistribution is associated to a different heat transfer between the different areas, and that different heat transfer could be related to the mass flow but also with the refrigerant quality at the evaporator inlet.

As a first approach it could be said that the thermography could give information about the heat ratio between the different parts of the heat exchanger but there are several combinations of mass flow maldistribution and quality maldistribution which could represent that behavior.

The test matrix followed in order to analyze the phenomena has covered a wide range of test conditions changing the superheat (SH) from 0 K to 15 K and the inlet vapor quality from 0.04 to 0.3 for water temperature differences of 5 K and 13 K. totaling a set of 32 experimental points where the refrigerant maldistribution was measured.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Table 2 and Table 3 shows the experimental results obtained for a water temperature difference and different vapor quality and superheat.

**Table 2.** Thermography results obtained for the case in which the water temperature difference is 5 K. For each case the evaporating temperature and the temperature difference between the refrigerant and the water at the outlet of the evaporator is supplied.

<table>
<thead>
<tr>
<th>SH=0</th>
<th>SH=5</th>
<th>SH=10</th>
<th>SH=15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevap=12.34°C</td>
<td>Tevap= 10.34 °C</td>
<td>Tevap= 9.00 °C</td>
<td>Tevap= 4.61 °C</td>
</tr>
<tr>
<td>x=0.07</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tevap= 12.81 °C</td>
<td>Tevap= 8.37 °C</td>
<td>Tevap= 7.39 °C</td>
<td>Tevap= 4.61 °C</td>
</tr>
</tbody>
</table>
Table 3. Thermography results obtained for the case in which the water temperature difference is 13 K. For each case the evaporating temperature and the temperature difference between the refrigerant and the water at the outlet of the evaporator is supplied.

<table>
<thead>
<tr>
<th>SH</th>
<th>Tevap</th>
<th>DT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4.04 °C, DT=3 K</td>
<td>1.02 °C, DT=8 K</td>
</tr>
<tr>
<td>5</td>
<td>4.81 °C, DT=8.8 K</td>
<td>5.97 °C, DT=1 K</td>
</tr>
<tr>
<td>10</td>
<td>6.20 °C, DT=0.8 K</td>
<td>5.26 °C, DT=3.5 K</td>
</tr>
<tr>
<td>15</td>
<td>6.45 °C, DT=9.3 K</td>
<td>6.07 °C, DT=9.4 K</td>
</tr>
</tbody>
</table>

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From these figures the following statements can be done:

- The two-phase flow region can be identified by a sharp change in color from yellow/green to red.
- The measured evaporation temperature is approximately 2 K lower than the minimum surface temperature registered by the camera.
- In the points with superheat, the two-phase flow region is not even distributed, indicating a maldistribution of the refrigerant mass flow. The right or the central part of the heat exchanger has a larger fraction of the heat exchanger at lower temperature. This indicates that a larger amount of liquid refrigerant in passing through this part of the heat exchanger.
- The points with 0 K superheat show a quite similar evaporation temperature independently of the refrigerant inlet quality. This fact with the low temperature difference between the refrigerant and the water points to a more uniform distribution.
- The inlet quality influences the distribution in a complex way. For qualities close to 0 and qualities about 0.3 the degradation of the system performance with the superheat is smaller than for the quality values between them. The possible explanation could be related to the distribution system, which probably is optimized for vapor qualities of 0.3, then as we go further from these values the refrigerant distribution will be worst. The improvement at low vapor qualities could be related to the fact that at these conditions all the refrigerant is almost in liquid phase. In fact, in these conditions the observed pattern is different to the rest, the refrigerant tends to accumulate in the middle of the heat exchanger and the last channels are with a small quantity of liquid refrigerant.
- For higher superheats the two-phase flow area is smaller than for lower superheats.
- Comparing both tables, the degradation of the BPHE performance is higher at higher water temperature differences.
Figure 4. Evaporating temperature for the tested points as a function of superheat for the different inlet qualities and water temperature difference of 5 K (left) and 13 K (right).
Other relevant point of this analysis is the way in which maldistribution could affect the efficiency of the heat exchanger. In order to analyze this point Figure 4 represents the evaporation temperature as a function of superheat for the different qualities and water temperature differences. In addition, the data obtained for the heat exchanger behavior in case of having an homogeneous distribution has been included. These data has been calculated using the modeling software IMST-ART(Corberan et al (2002)).

As can be observed, the experimental values are in general much lower than the calculated ones. The agreement between calculated and measured values is only good and null superheat. At those conditions, however, it seems there is still a deviation with lower evaporation temperatures in the test points with the lowest inlet qualities, with a high deviation for dTw=13K and inlet quality \( x = 0.07 \).

On the other hand, independently of the water temperature drop, both calculated and measured values are almost coincident when the evaporation temperature is controlled by the superheat, with an evaporation temperature very close to Twin-SH. When the superheat is very high, the evaporation temperature is controlled by it, and the fact that most of the evaporator area is dedicated to superheating the refrigerant the maldistribution of refrigerant, although present, it makes no further penalty on the evaporation temperature. This is also possible to be distinguished in the thermographies, where, at the highest superheats, the outlet of zone 2, which we assumed with a high content of liquid refrigerant, is seen as superheated.

It is also interesting to note that for dTw=5K, the cases with high quality inlet, 0.2 and 0.3, also present a good agreement with the calculated results, clearly indicating a lower penalty due to the maldistribution. However, at dTw=13K this is only appreciable at inlet quality 0.3, which clearly presents a penalty lower than the other inlet qualities. Therefore, the penalty due to the maldistribution depends on the inlet quality.

Trying to analyze in a deeper way and observing the thermography’s, it is seen that there is one region in which the evaporator has a lower temperature value which probably is associated with a higher amount of refrigerant through these channels. Based on that observation, in order to analyze the results, the heat exchanger decomposition shown in figure 5 can be done. The figure shows that when the obtained maldistribution is present, the BPHE behavior will be more similar to a configuration in which two heat exchangers are working in parallel than with only one heat exchanger. In that scheme the heat exchanger corresponds with figure 5 where the BPHE N2 represents the heat exchanger with the higher heat transfer ratio and N1 represents a heat exchanger with the rest of the area and with a net heat transfer pondered to the rest of the heat exchanger. It should be noted that in this approach the heat transfer process will be governed mainly by N2.

![Diagram](image)

**Figure 5.** Scheme of the approach developed in order to reproduce the heat exchanger behaviour. Refrigerant side (left) and water side (right)

Based on that scheme and considering that the maldistribution problem will be less noticeable (if exist) on the water side than in the refrigerant side, when the refrigerant maldistribution is present it will reduce the water temperature in these channels more than the rest of the heat exchanger and consequently this fact will have consequently a reduction in evaporating temperature on the refrigerant side affecting the efficiency of the system.
This observation is very important as it helps to understand that the decrease in efficiency in BPHE as a consequence of the maldistribution is associated more to the uneven flow distribution of the fluids than to the reduction of the effective heat exchange area. In that sense to consequences must be extracted, an increase of the number of plates in a heat exchanger can be due to a dramatic decrease of the heat exchanger performance if good refrigerant distribution is not guaranteed. On the other side, the refrigerant maldistribution effect could be reduced if it is compensated increasing the water flow in these channels, proper asymmetric heat exchangers or distributors on the water side could help on that direction.

Based on all these results, it is seen that maldistribution will introduce a higher penalty when the superheat is smaller than the water temperature drops and when superheat is high compared to the water temperature drop, the maldistribution although present will not have an important influence in the BPHE performance. This result is very relevant as nowadays in many applications water temperature drop is maintained at moderated values of 5 K but as the applications of heat pumps are grows more applications in which the temperature lift of the secondary fluid can be larger, like heat recovery applications, and the performance of these systems could be reduced significantly.

4. CONCLUSIONS

In this work, an analysis of refrigerant maldistribution in a BPHE evaporator using thermography has been presented. This technic although is not useful in order to determine the mass flow in each channel supply information about the heat transfer process inside the heat exchanger and allows to identify problems in its performance.

From all the developed work the following results have been obtained:

- The maldistribution does not seem to be very important for the condition 0 K.
- When maldistribution is present it does not affect the BPHE performance in the same way. When superheat is significantly higher than water temperature drops the presence of maldistribution do not have an important impact on the performance of the BPHE but when water temperature drop is comparable or larger than the superheat the degradation of the BPHE performance can be significant.
- The observed significant degradation can be associated to the uneven water temperature in the heat exchanger which significantly reduces the evaporating temperature. The observed degradation is higher than the corresponding only to a reduction of area, therefore, special care should be taken when the number of plates is increased in BPHE.

The observed effect of the maldistribution can be very significant conditions with large water temperature drop but according to the observed results it could be mitigated by a redesign of the heat exchanger in order to increase the water mass flow over the channels in which there is more refrigerant passing through them. Other alternative that could be tested is to have the inlet of the water and the refrigerant in different faces of the heat exchanger.

Other alternative, in order to reduce the maldistribution effects, overall at large water temperature drops, can be to work with an accumulator at the outlet of the evaporator in such a way that the superheat would be reduced to 0 K. In that configuration no maldistribution effect has been observed.

Nowadays the group is working in the development of a detailed model which allows the determination of the quality and the mass flow through the channels based on the observed values of the thermography’s and on the definition of a procedure to characterize this phenomenon in order to be able to perform predictions of the results.

NOMENCLATURE

The nomenclature should be located at the end of the text using the following format:

- m: mass flow (kg/s)
- x: refrigerant quality (-)
- SH: superheat (K)
- β: fraction of refrigerant mass flow through the virtual heat exchanger 2 (-)
- α: fraction of water mass flow through the virtual heat exchanger 2 (-)
- DT: Temperature difference between heat exchanger water outlet and evaporating temperature. (K)
DTw \hspace{1cm} \text{Water temperature decrease on the evaporator (K)}
\[N\] \hspace{1cm} \text{number of plates on the virtual heat exchanger (--)}

\begin{itemize}
  \item \textbf{Subscript}
  \begin{itemize}
    \item ref \hspace{1cm} \text{refrigerant}
    \item w \hspace{1cm} \text{water}
    \item evap \hspace{1cm} \text{evaporating}
  \end{itemize}
\end{itemize}

5. REFERENCES


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