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## Analysis of the refrigerant maldistribution of propane evaporating in brazed plate heat exchangers as a function of operating conditions

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### Abstract

One of the most common factors affecting the performance of brazed plate heat exchangers (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 and the deviations in other conditions 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. BPHE has been tested and evaluated working at several inlet conditions (quality) and outlet conditions, the refrigerant distribution inside the BPHE has been registered using thermography. From this analysis an estimation of the influence of the refrigerant maldistribution in the system performance has been obtained.

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### 1. Introduction

The use of braze 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. Maldistribution was quickly observed as higher demands and bigger heat exchangers were needed. In that sense, BPHE evaporators are very sensitive to uneven distribution of the refrigerant among the different plates because of the fact of having two phase flow in their inlet port. As a consequence of that, the heat transfer can be highly degraded affecting significantly to the global system performance.

The precise determination of the real refrigerant mass flow in each plate is difficult but some research has been done in the qualitative estimation of it based on infrared thermography. This technic can be applied because of the fact that the refrigerant/water temperature in each plate would have a different profile depending on the vapor/liquid refrigerant distribution in each channel.

From the early literature on the plates arrangements on flow distribution is presented by boasiouny et al [1, 2] where results indicate that manifold diameter and number of channels have great influence in maldistribution. Maldistribution causes higher or lower thermal performance degradation depending on if it is a U-type or Z-type heat exchanger. Z-type plate arrangement have more tendency to suffer maldistribution, see Tonon et al. [3].

The quality distribution in heat exchanger manifolds were investigated by Vist et al. [4] 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 take into account to have mass flow evenly distributed within the channels. For high mass flow and low inlet quality, better distribution is mentioned by many researchers [5,6]. 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 et al., are perfectly separated [7].

For microchannel heat exchangers, Elbel et al. [8] proposed an improvement for achieving better refrigerant distribution. The solution consisted in remove flash gas; vapor phase is separated from liquid phase after the expansion valve. In this way, only liquid is flowing within the microchannel heat exchanger while the vapor phase is being bypassed. Thermography pictures showed clear more uniformly distributed superheat with this flash gas removal system. Furthermore, better system performance was observed when using the separation device. Although quality maldistribution can be reduced in some cases introducing some modifications in the inlet, Tou et al. [9] reported that the outlet header pressure drop can have an influence in the mass flow rate maldistribution from tube to tube.

As mentioned before, 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, or Longo [10, 11] used thermography in microchannel heat exchangers to visualize the two-phase flow region for different outlet vapour 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.

Regarding BPHE, although the problem is known [6] and some solutions has been adopted by the main manufacturers in order to achieve a better refrigerant distribution, see for instance [12] where a system that feeds homogeneously with refrigerant all channels has been developed or the introduction of what is call equalancer distributor in order to improve the refrigerant distribution [13], from the practical point of view, there is not a final totally satisfactory solution for this problem. In fact, the intrinsic design characteristics of this type heat exchanger made that the analysis of the refrigerant distribution more difficult to carry on and the detailed examination of the maldistribution from the experimental point of view is challenging. This has made that the amount of information in the open literature of this kind of phenomena for this type of heat exchanger is significantly less than for other heat exchangers like tube and fin or microchannel heat exchangers.

In this paper, the refrigerant maldistribution problem in BPHEs is going to be analyzed as a function of different operation parameters like evaporator inlet quality, evaporator superheat and water temperature difference. The analysis has included a wide test campaign in which the refrigerant distribution in the evaporator has been characterized at different working conditions using infrared thermography. Later on the influence of the refrigerant maldistribution in the system performance has been evaluated in such a way that the influence of this type of problem can be quantified.

## 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 scheme of the heat pump is shown in figure 1. Between the condenser and the liquid receiver there is throttling valve, this valve allows the control of the subcooling at the outlet of the condenser. Its operation principle is shown in figure 1b, in steady state conditions, the liquid receiver must be in saturated conditions, this fact produces that changing the pressure drop introduced by the throttling valve, the system is able to control the amount of refrigerant inside the liquid receiver and the heat pump subcooling. In order to measure the subcooling, it was made measuring the temperature and the pressure at the outlet of the condenser. Between the liquid receiver and the evaporator there is an electronic expansion valve which allow the control of superheat. In a similar way the determination of superheat was done measuring the temperature and the pressure at the compressor inlet, it was assumed that the pipe from the evaporator to the compressor was short enough in order to assume that these conditions would be the conditions at the evaporator outlet. This experimental set up allows the stable control of the vapor quality at the evaporator inlet (subcooling at a condensing temperature) and the superheat at the evaporator outlet.

The system topology shown in figure 1 only allows working in stable conditions at superheats higher than 5K. In order to work in saturated conditions, the heat pump shown in Figure 1 has been modified.

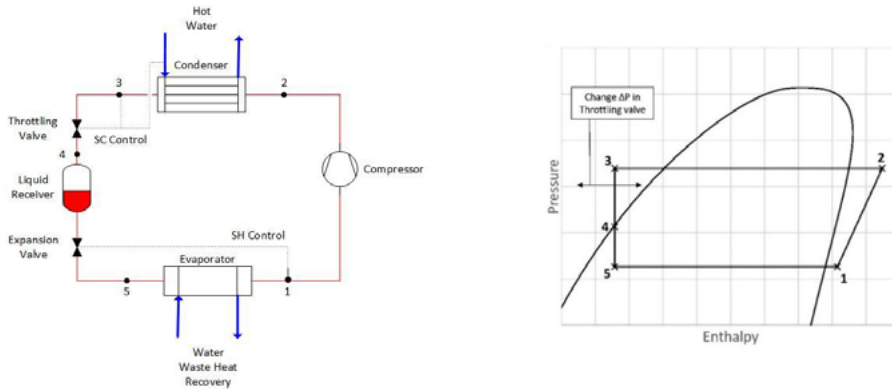


Figure 1. Mode 1 configuration system lay-out and refrigerant cycle

Figure 2 shows the other working alternative which allows working with 0 K superheat. In this configuration, a by pass system has been installed in the heat pump in such a way that the liquid receiver is placed at the outlet of the evaporator

the expansion valve is dedicated to control the subcooling at the expense of losing the superheat control which is fixed to 0 K. In this sense, the liquid receiver is placed at the outlet of the evaporator (point 5) ensuring saturated vapor conditions at compressor inlet (zero superheat). The expansion valve is removed from the system and therefore the superheat will be not controlled and the only heat pump control is related to the subcooling.

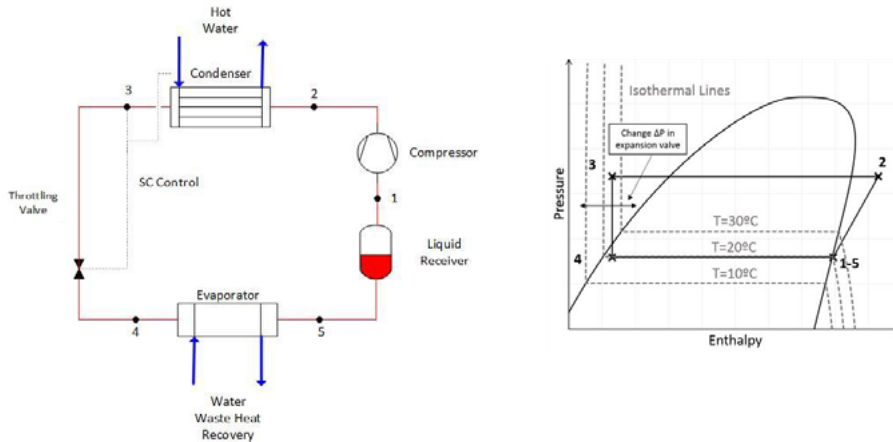


Figure 2. Mode 2 configuration: system lay-out and refrigerant cycle

Figure 3 shows a scheme of the test unit with all the instrumentation used. The green box corresponds to the BHPE evaporator. The main characteristic of it are 120 plates, capacity of 40 kW capacity at the nominal point, a horizontal port distance and vertical port distance of 50 mm and 466 mm respectively resulting a 6 m<sup>2</sup> heat transfer area.

There is a water loop in the condenser and in the evaporator, each water loop has a temperature sensor at the inlet and outler of the water side and have a Coriolis mass flow meter to measure the water mass flow rate. The water pumps of each circuit are equipped with an inverter which adjusts the water mass flowrate in such a way that the water temperature difference can be maintained as constant. These two water loops are connected to a third one which allows to control the water temperature inlet in both heat exchangers. More detailed information about this system can be found in [14].

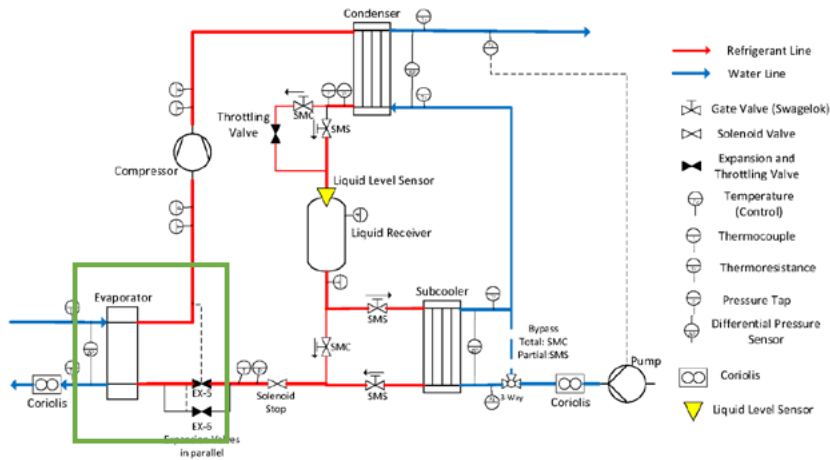


Figure 3. Propane Water-to-water heat pump in which the refrigerant distribution in the evaporator has been tested.

Regarding the refrigerant circuit, two temperature sensors are placed in each inlet and outlet of both heat exchangers. Three Rosemount sensors are installed in the refrigerant side, at the compressor inlet and outlet and in the liquid receiver. The last pressure sensor constitutes a way to verify the subcooling value. The mass flow rate in the refrigerant side is determined by means of a heat balance between the water side and the refrigerant side. In order to monitor and measure the parameters on the BHPE, all the sensors were connected to a data acquisition system “Agilent 34970A”, where all parameters were monitored. The relative and absolute accuracy of each device are shown table 1.

Table 1. Instrumentation used in the test rig

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

To register the refrigerant distribution, the surface of the evaporator is been photographed using the camera FLIR P640 infrared camera. The accuracy of the camera is shown in table 1, it should be also commented that although the estimation of the exact temperature has a higher error than an RTD, the sensibility of the camera is of 30mK, therefore although quantitative test could present significative deviations from the reality, under the proper, the camera would be able to supply a qualitative representation of the heat transfer process in the BPHE. The IR camera was set to a measuring range of -40 to 120°C.

Figure 3 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.

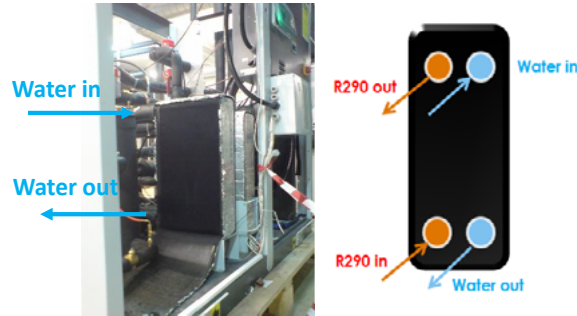


Figure 3. Picture of a frontal view of the evaporator and a transversal view with the location of the inlet/outlet ports

With this experimental setup and after the pre-evaluation and literature research on the relevant aspects that could affect the refrigerant distribution in the evaporator, the points represented in the test matrix shown in figure 4 where measured. The refrigerant distribution in the evaporator was evaluated for evaporator outlet superheat (SH) from 0 K to 15 K and the evaporator inlet quality (x) for a water temperature difference in the evaporator of  $dT_{water}=5$  K and  $dT_{water}=13$  K with a water inlet temperature of 20°C.

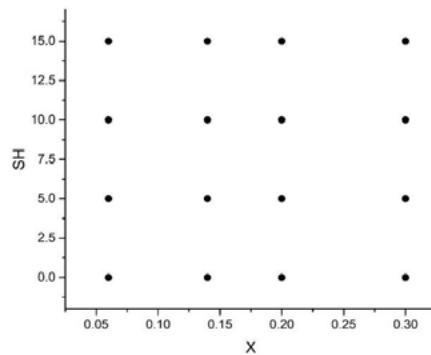


Figure 4. Experimental measures points for  $dT_{water}= 5$  K and  $dT_{water}= 13$  K

### 3. Obtained Results

Table 2 and table 3 shows the corresponding IR thermographies for a water temperature difference of 5 K and 15 K respectively. They are given in tables in the corresponding order of superheats. The minimum temperature of the scale is set to -6°C and the maximum to 20°C. The same scale is maintained for both sets of data in order to be able to stablish comparisons among them.

The values shown in the different columns represents different superheats and the values represented in the different files represents different evaporator inlet qualities.

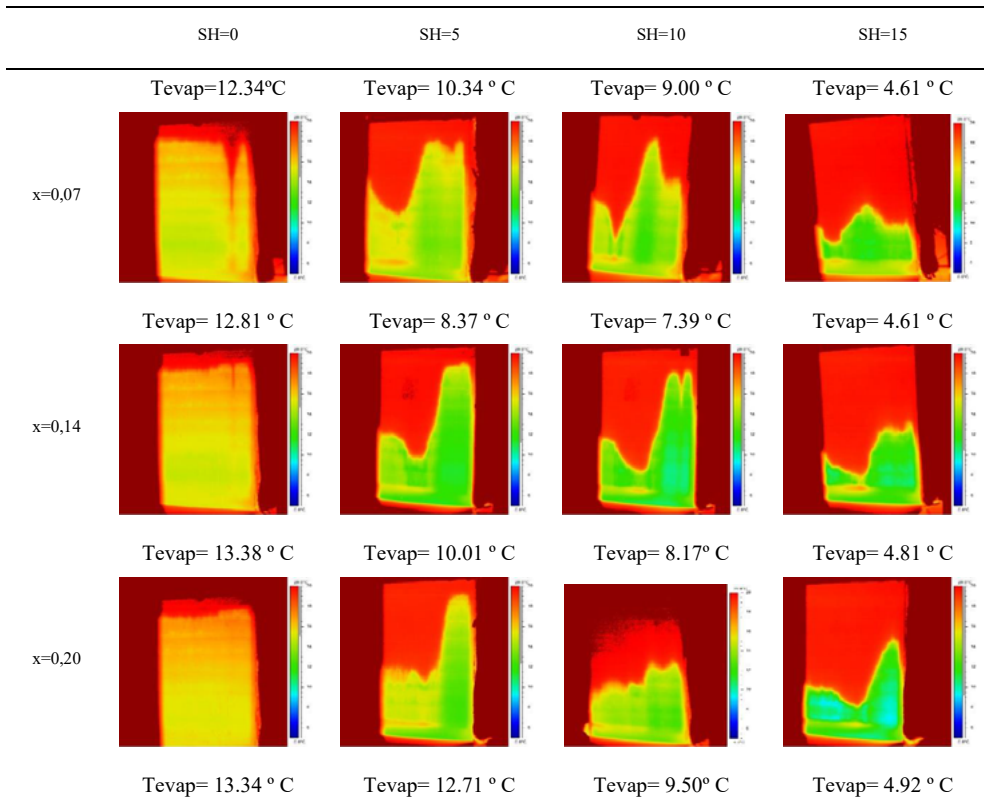
In order to evaluate the maldistribution influence in the system performance, the evaporation temperature ( $T_{evap}$ ) has been selected as the basic indicator parameter.

The points can be observed in the thermography pictures presented in table 2 and table 3:

- The two-phase flow region can be identified by a sharp change in color from yellow/green to red.
- The minimum temperature in table 3 are smaller than in table 2.

- 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 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.
- 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 the 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.
- 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.

Table 2. Thermographies for  $dT_{water} = 5$  K with variation of inlet quality and superheat



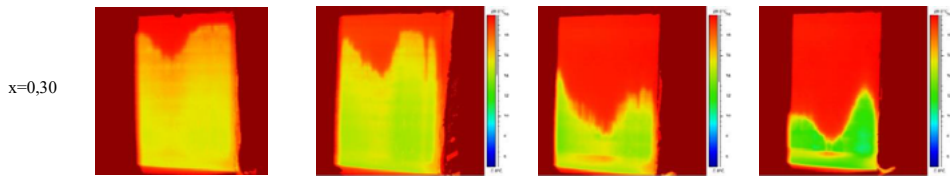


Table 2. Thermographies for  $dT_{water} = 13\text{ K}$  with variation of inlet quality and superheat

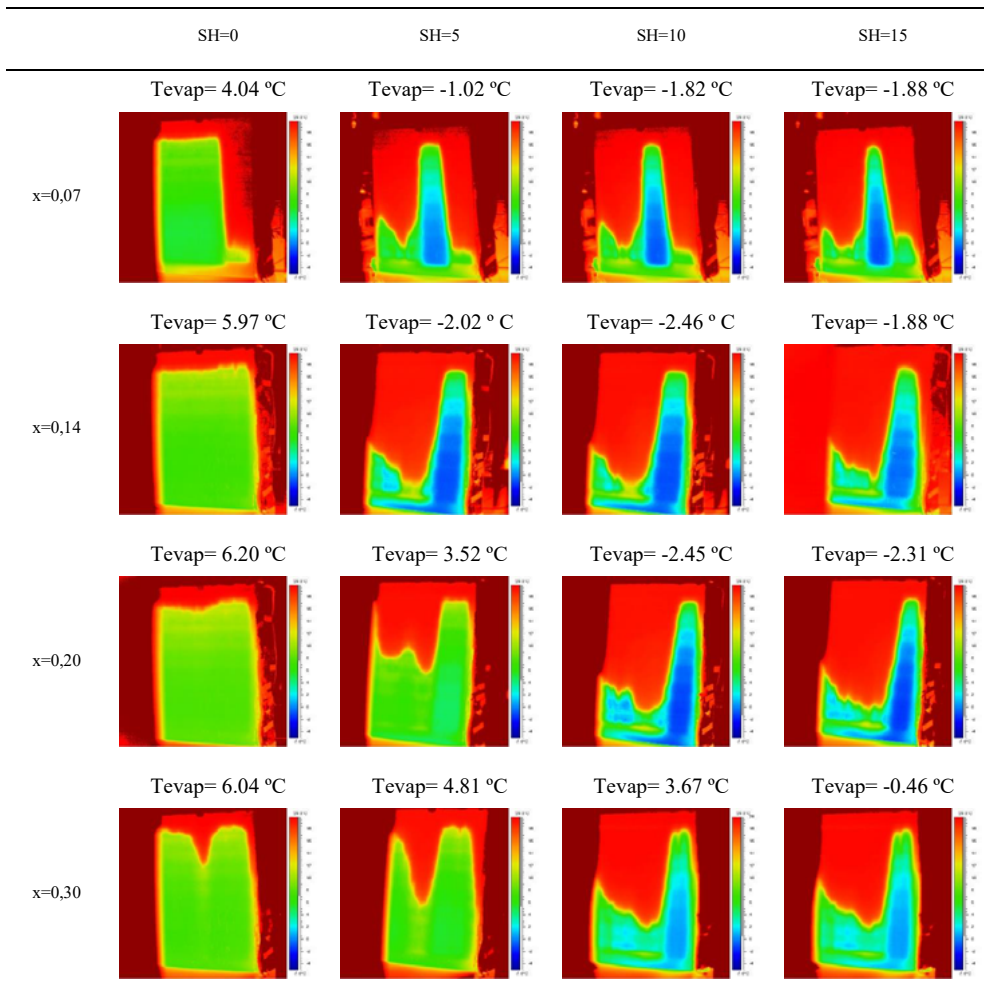


Figure 5 represents the evaporation temperature as a function of the vapor quality and superheat for both sets of experiments. In that figure 5 (left) can be observed that evaporation temperature is almost independent of vapor quality except when superheat have a value comparable or lower than the water temperature difference. If the maldistribution of the refrigerant depends on the refrigerant quality at the evaporator inlet and it is

independent of the water side, the information obtained from figure 5 (left) points to the fact that, although there is a maldistribution it do not have a direct influence on the heat exchanger performance as the evaporating temperature do not change significantly. In figure 5 (right) the results are not so clear, but it can be stated that the obtained results depend in all the working map on the superheat and on the vapor quality.

A possible explanation could be related to the fact that in figure 5 (right) water temperature lift is similar or higher than the superheat in all the cases. Based on that hypothesis, the performance of the heat exchanger will be affected by the maldistribution problem when water temperature lift is higher than superheat, and in these cases the vapor quality at the inlet will have influence on the heat exchanger performance.

Based on that explanation for the obtained results, it can be determined that refrigerant maldistribution could increase its effects in the degradation of the heat exchanger performance in applications where the temperature difference in the secondary fluid side could be high like when the heat pump evaporator is used in heat recovery applications with a finite source of low temperature heat in order to produce heat at high temperature.

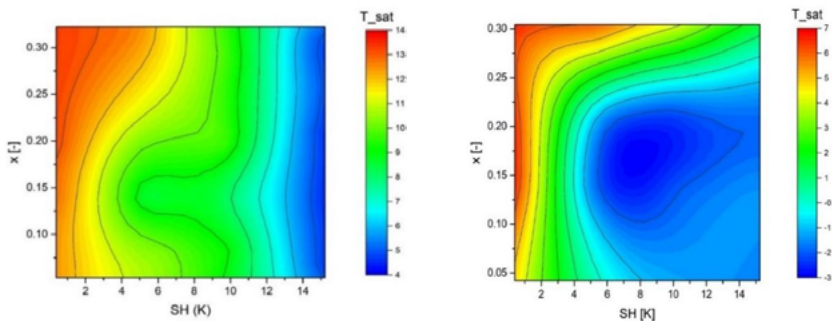


Figure 5. Saturation temperature for  $dT_{\text{water}} = 5$  K (left). Saturation temperature for  $dT_{\text{water}} = 13$  K (right)

#### 4. Conclusions

Maldistribution in a brazed plate heat exchanger has been experimentally observed with infrared thermography. When maldistribution occurs, evaporator surface temperature is distributed unevenly and can be registered with thermography as it is non-intrusive and non-contacting, having no influence in the evaporator. Inlet quality and superheat has been changed during the tests for a given water temperature difference to observe this phenomenon.

As observed in the thermography pictures (figures 2 and 3), inlet quality has an influence in maldistribution at first sight. For high inlet quality, better refrigerant distribution is observed. However, superheat is observed to have a minor effect. The higher the superheat, better distribution is shown in the thermography for a 5 K water temperature difference. Most homogeneous temperature map distribution is achieved when no superheat is performed.

Evaporation temperature has a great impact in system efficiency. Were the evaporator forced to work with a high level of superheat, less area is available for evaporation thus, evaporation temperature decreases. As expected, higher evaporation temperature is achieved when both low superheat and high inlet quality refrigerant is flowing. Although maldistribution is observed in thermography, underperformance is not inherited to all the cases. Related to that it is crucial to be able to determine how the maldistribution influence the performance of a BPHE as in some applications it could be higher than expected. In fact maldistribution have a higher influence in system performance when water temperature differences are equal or higher than superheat. This could be a relevant factor to take into account in applications where there is a high temperature difference on the secondary fluid like heat pumps used for energy recovery applications based on waste heat sources of finite availability.

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