Applied Thermal Engineering 73 (2014) 877–885

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Mitigation of air flow maldistribution in evaporators

Christian K. Bach*, Eckhard A. Groll, James E. Braun, W. Travis Horton

Department of Mechanical Engineering, Purdue University, West Lafayette, IN, USA

HIGHLIGHTS

- Interleaved circuitry shown to reduce effects of flow maldistribution in evaporators.
- Approach greatly reduces capacity degradation, similar to individual circuit control.
- Incorrect choice of paired circuits can, in the limit, eliminate benefits.

ARTICLE INFO

Article history:
Received 7 May 2014
Accepted 2 August 2014
Available online 8 August 2014

Keywords:
Flow maldistribution
Evaporator
Hybrid control
Individual circuit flow control

ABSTRACT

Flow maldistribution in evaporators can lead to significant performance and capacity degradation. A significant amount of work has previously been published to overcome this issue. For a fixed air side maldistribution, various methods have been proposed to significantly reduce the effect on performance. Refrigerant compensation has been proposed to reduce the effects of maldistribution in variable air flow systems. However, little work has been found in open literature relative to modifying the refrigerant circuitry to make it less vulnerable to variable air-side maldistribution. The purpose of this paper is to fill this gap in the open literature with a simple and easy to understand case study. The performance of a proposed interleaved circuitry approach, and active refrigerant flow control are compared to standard coil circuitry for different cases of maldistribution. The results show that the interleaved circuitry recovers less of the performance losses than equalization of the exit superheats by active control of refrigerant distribution. However, the implementation cost in an actual system is expected to be much lower and the long term reliability is expected to be better than for an active control approach

1. Introduction and motivation

Evaporators are used in vapor compression systems under various operating conditions, which may include air-side flow maldistribution, air-side temperature maldistribution, dust and organic matter leading to uneven fouling, and (uneven) frost build-up for low air inlet temperatures.

1.1. Air-side maldistribution

If care is taken during the design phase of the overall system, the evaporator design can be optimized to yield the best possible performance at a specified condition. An example of this can be found in Ref. [21]; they optimized the evaporator circuitry for a rooftop air-conditioning (RTU) unit with air-side maldistribution using NIST's evolutionary algorithm optimization module (ISHED). However, in a significant number of applications, such as RTU's with air-side economizer, heat pumps (HPs) with outdoor coil fouling or frost build-up, and walk-in cooler refrigeration systems (WCRSs) with frost build-up, the air-side maldistribution is not constant but rather dependent on operating conditions. In addition to air-side maldistribution, the distribution of refrigerant in each circuit is often far from uniform. Based on our own experience, even new systems of the described type often still employ a simple parallel circuit layout. There are some systems that have limited overlap between circuits but it seems that the benefits of this overlap are, in general, not well known. The starting point of this paper was to show in a simple case study what benefits can be achieved by using a maximum overlap, termed interleaved circuitry.

1.2. Refrigerant-side maldistribution

[10] estimated the refrigerant-side maldistribution based on a combination of simulation and experiment for a WCRS. They found that individual circuit flow rate can differ by up to +51% and −61%

* Corresponding author.
E-mail address: christian.konrad.bach@gmail.com (C.K. Bach).

http://dx.doi.org/10.1016/j.applthermaleng.2014.08.010
1359-4311/

from the average circuit mass flow rate. They additionally found that maldistribution is depended upon operating conditions for this WCRS, which had a thermostatic expansion valve (TXV) connected directly to the distributor. Previously, Li (2001) performed simulation studies of numerous refrigerant distributors and found that the performance of the distributors depends on both the orientation of the orifice in the distributor as well as the direction of gravity. The best performance results were achieved when the center axis of the distributor was in line with the direction of gravity and the orifice was mounted without any tilt. According to the authors' own experience, distributors are typically not aligned with gravity and the inlet flow is often redirected before entering the distributor. Based on the authors own experience, exit superheat is very sensitive to the alignment between distributor and expansion device. Specifically, we noticed that for a 4-ton (14.1 kW) RTU, changes of approximately 1° in alignment result in a noticeable change of the individual circuit exit superheats. In a production type environment it is difficult to control the alignment to this degree.

1.3. Active refrigerant flow distribution

Several research groups investigated active control of refrigerant flow distribution to optimize evaporator performance. The two main approaches are a commercially available expansion distribution device [6] and a hybrid control approach, initially introduced by Ref. [15]. In the commercial product, the expansion distribution device periodically supplies refrigerant to each of the circuits using a rotating disc mechanism. The time-fraction of refrigerant supply to each circuit is adjusted based on an algorithm that evaluates the overall exit superheat. Unfortunately detailed results of the performance of this device are missing in the open literature. The hybrid control approach employs a two stage expansion process, where most of the pressure drop occurs in the primary expansion valve while small balancing valves are used to distribute the refrigerant between circuits. The common result of experimental and simulation studies that have investigated the benefits of adjusting refrigerant flow rates to individual circuits ([3,12–19] to name a few) is that the majority of the performance losses can be recovered if refrigerant flow distribution is actively controlled. In general, system level performance as well as evaporator capacity decreases with increasing maldistribution. The impact can be significant –[19], for example found capacity reductions of up to 41% and 32%, respectively, for wavy and wavy lanced fin evaporators if overall superheat was held constant while the individual circuit superheats were allowed to vary. All of the research papers found in the open literature on this topic note that a recovery to within a small percentage of the original capacity is possible if individual circuit mass flow rates are controlled to achieve equal exit superheats. One interesting result that should be pointed out is that [13] found that the maximum performance recovery was achieved at nonuniform exit superheats for their 2-circuit simulation model. Note that refrigerant flow distribution needs to be controlled at the inlet of the evaporator (upstream control) and not by throttling of the refrigerant exiting the evaporator (downstream control). [17] found that downstream control leads to a penalty over the baseline case without active flow control if airside flowrates were unequal between circuits. This was caused by a reduction of the compressor suction pressure, which decreases capacity and COP. If the flow is controlled before the refrigerant enters the evaporator, then the compressor suction pressure was nearly identical for both, baseline case without maldistribution and upstream control with applied maldistribution. All other previously mentioned works employed different forms of upstream control, using needle valves, EXV, and a rotating disk expansion distribution device.

1.4. Passive compensation

Kaga et al [11] simulated the effects of varying the downstream circuitry length for a 24 tube 2-circuit, 2-row evaporator under air flow maldistributed conditions. They found that increasing the downstream circuitry length leads to a reduction of the capacity losses from 6% to less than 1%. These results were obtained for a case in which the top half of the evaporator had a 50% higher flow rate than the bottom half. The increase in downstream circuitry length simultaneously increased the overlap between the two circuits in the airflow direction from 0% (case 1) to more than 60% (case 2).

1.5. Motivation

Refrigerant-side and air-side maldistribution are significant issues for vapor compression systems that need to be addressed to further improve the efficiency of equipment for applications where time-varying maldistribution can occur during operation. This paper demonstrates a simple approach for effectively handling maldistribution, termed “interleaved circuitry”, and compares its performance against active control of the exit superheats as well as the baseline circuitry layout.

2. Case study with a two-circuit evaporator

To gain a general understanding of how interleaved circuitry works, consider an evaporator with 2 circuits as shown in Fig. 1. Refrigerant enters the circuits on the left, while air enters the circuits on the right to achieve cross counter flow operation. This evaporator type is subsequently referred to as a standard evaporator. If no air-side or refrigerant-side maldistribution is present, this configuration is closest to cross flow and therefore leads to a good usage of the given evaporator surface area. However, if air-side maldistribution is present, the effectiveness of the heat exchanger changes. Fig. 1 shows that a larger air flow rate and/or air inlet temperature for circuit 1 leads to a larger superheat at the exit of this circuit than for the other circuit. The extent of this difference depends on how much the two air flow rates and temperatures differ.

2.1. Hybrid evaporator

Fig. 2 shows how active refrigerant flow control (such as an expansion-distribution valve or the hybrid control concept) reacts to air-side maldistribution: the refrigerant flow rates are adjusted to lead to approximately the same exit superheat for each circuit. This evaporator is subsequently referred to as a hybrid evaporator to distinguish it from the standard evaporator that has identical circuitry but no active flow control.

2.2. Interleaved evaporator

Fig. 3 shows the interleaved evaporator. The refrigerant from the top circuit is redirected to the bottom and vice-versa. In the non-maldistributed case, there is not much difference in capacity

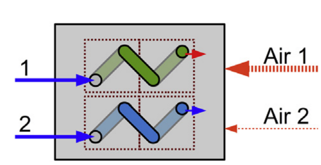

Fig. 1. 2-Circuit evaporator with air side maldistribution (“Standard”).