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Experimental investigation of the effects of airflow nonuniformity on performance of a fin-and-tube heat exchanger

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ABSTRACT

The effects of airflow nonuniformity on the thermal–hydraulic performance of a fin-and-tube heat exchanger were investigated experimentally. The test subject was a four-depth-row fin-and-tube heat exchanger with face split tube circuitry. Nonuniform inlet air distribution was generated by partially blocking the heat exchanger entrance cross-section. It was found that airflow nonuniformity causes thermal effectiveness deterioration and pressure drop increase. The size of effectiveness deterioration and pressure drop increase depend on the degree of airflow nonuniformity as well as on the orientation between airflow nonuniformity and tube-side fluid circuitry. For most of the observed nonuniform airflow profiles, which had low or moderate degrees of airflow nonuniformity, the effectiveness deterioration was between 5% and 10%, while the pressure drop increase was between 10% and 20%. For severely nonuniform airflow profiles the effectiveness deterioration was up to 30% and the pressure drop increase was up to 90%.

Etude expérimentale des effets d'écoulement d'air non uniforme sur la performance d'un échangeur de chaleur à tube à ailettes

Mots clés : Etude expérimentale ; Echangeur de chaleur à tube à ailettes ; Non uniformité de l'écoulement d'air ; Détérioration de l'efficacité ; Augmentation de la chute de pression

1. Introduction

Fin-and-tube heat exchangers find extensive application as evaporators and condensers in residential and commercial heating, air-conditioning and refrigeration or as air-cooled heat exchangers in the transport, process and power industry. The performance of fin-and-tube heat exchangers is strongly affected by the airflow distribution that is usually nonuniform at the entrance. Causes of airflow nonuniformity are poor design of the inlet and outlet

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Nomenclature

A	surface area, m^2
C	heat capacity rate, $W\ K^{-1}$
C^*	heat capacity rate ratio, C_{min}/C_{max}
c_p	specific heat capacity, $J\ kg^{-1}\ K^{-1}$
d_c	collar diameter, $d_o + 2\delta_f$, m
d_o	tube outside diameter, m
d_i	tube inside diameter, m
h	heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
k	thermal conductivity, $W\ m^{-1}\ K^{-1}$
L	length, m
$\dot{m}$	mass flow rate, $kg\ s^{-1}$
N	total number
NTU	number of transfer units
Δp	pressure drop, Pa
Δp^*	pressure drop increase
Q	heat transfer rate, W
T	temperature, K
U	overall heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
V	volumetric flow rate, $m^3\ s^{-1}$
w	fluid velocity, $m\ s^{-1}$
w	average fluid velocity, $m\ s^{-1}$

Greek

ε	heat exchanger effectiveness
$\Delta\varepsilon$	effectiveness deterioration
δ_f	fin thickness, m
η	extended surface efficiency

Subscripts

a	air
in	inlet
max	maximum
min	minimum
nonunif	nonuniform airflow profile
out	outlet
unif	uniform airflow profile
w	water

headers, heat exchanger operating conditions, fouling and geometrical imperfections on the heat exchanger surfaces, see for example Kitto and Robertson (1989); Mueller and Chiou (1988); Shah and Sekulić (2003); Singh et al. (2014).

The performance of fin-and-tube heat exchangers subject to airflow nonuniformity have been extensively investigated with analytical approaches (Beiler and Kröger, 1996; Chiou, 1978; Domanski and Yashar, 2007; Jiang et al., 2006; Lee et al., 2003; Mao et al., 2013; Ranganayakulu and Seetharamu, 1999) and numerical modeling (Aganda et al., 2000; Hoffmann-Vocke et al., 2009; Kærn et al., 2011a; Lalot et al., 1999; Yaïci et al., 2014). These studies reported that airflow nonuniformity reduces the heat exchanger thermal performance by up to 30%. The size of the thermal performance loss depends on the heat exchanger operating point (i.e. the ε–NTU–C^* relation), the flow arrangement between fluids, the degree of airflow nonuniformity and the airflow regime. Furthermore, the thermal performance of evaporators and condensers is also affected by the mechanism controlling the refrigerant flow rate as it has been seen that airflow nonuniformity can induce tube-side maldistribution (Domanski and Yashar, 2007; Kærn et al., 2011a). Concerning the heat exchanger hydraulic performance, the pressure drop that results from nonuniform airflow can be several times that of uniform airflow (Hoffmann-Vocke et al., 2011; Mao et al., 2013; Ranganayakulu et al., 1996). Unlike analytical and numerical studies, experimental studies about the effects of airflow nonuniformity on the performance of fin-and-tube heat exchangers are rather scarce.

Chwalowski et al. (1989) found that nonuniform air distribution reduces the thermal performance of air-conditioning evaporators by 30% in the worst case. Choi et al. (2003) concluded that nonuniform air distribution reduces the evaporator capacity by up to 8.7%, while refrigerant maldistribution alone reduces the capacity by as much as 30%.

Yashar and Domanski (2010) and Yashar et al. (2011) used PIV technique for measuring air velocity profiles in residential air-conditioning heat exchangers. Measurements revealed nonuniform air distributions at the heat exchanger entrance. The heat exchanger obstructing features (condensation collection hardware and mounting brackets) are found to be the dominant sources of this airflow nonuniformity. T'Joen et al. (2006) measured the impact of nonuniform air distribution on the thermal performance of a fin-and-tube heat exchanger. They found that the overall heat transfer coefficient is reduced by 8.2% for a quadratic air profile and by 3.6% for a parabolic air profile. The degree of airflow nonuniformity, defined by Eq. (12), was 0.55 for the quadratic profile and 0.37 for the parabolic profile. The previously cited experimental studies agree that nonuniform air distribution causes loss of thermal performance in heat exchangers, the size of which increases with the degree of airflow nonuniformity. However, these general conclusions are opposed by two studies (Kirby et al., 1998; Timoney and Foley, 1994), which found an improvement of thermal performance in heat exchangers subject to nonuniform airflow. Timoney and Foley (1994) found that the evaporator cooling capacity increased between 3% and 4.5% for two out of the three imposed nonuniform airflow profiles. The evaporator was a four-depth-row fin-and-tube heat exchanger with 33 tubes in a single circuit. According to the two researchers, the turbulence intensity in nonuniform airflow is causing higher overall heat transfer coefficients and thus higher evaporator capacity relative to those of uniform air distribution. Kirby et al. (1998) analyzed the effects of airflow nonuniformity on the thermal performance of a residential air-conditioning evaporator under dry and wet operating conditions. The evaporator was a three-depth-row fin-and-tube heat exchanger with 45 tubes in three face split circuits. For dry conditions, seven out of the nine nonuniform airflow profiles increased the evaporator capacity by up to 2%. For wet conditions, no differences in the evaporator capacity were observed.

Airflow nonuniformity can lead to discrepancies between the predicted and the observed performance of heat exchangers. The existing experimental data about the effects of airflow nonuniformity are scarce and contradictory. The hydraulic per-