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Heat transfer and friction characteristics of fully developed gas flow in cross-corrugated tubes

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ABSTRACT

This experimental study is concerned with gas–liquid heat exchangers relying on cross-corrugated tubes. The experiments are carried out with air flow on the inner side of the tube, cooled by a secondary outer water flow. Overall 18 different geometrical configurations are investigated. In contrast to Harleß et al. (2016) the emphasis of the present investigation is put on the cross-corrugated variant. The dimensionless corrugation pitch p/d_i varies between 0.283 and 1.117, the dimensionless corrugation height e/d_i between 0.024 and 0.087, and the corrugation angle φ between 14.7° and 48.8°. The examined Reynolds number range is $5000 < \mathrm{Re} < 23{,}000$, to match a typical range of gas–liquid heat exchangers. Nusselt number and friction factor are plotted for all tubes and are correlated with a power law of the corrugation dimensions. Finally, the thermal performance of the tubes is investigated in terms of the $R3$ criterion. Within this study the highest thermal performance is obtained by a cross-corrugated tube with $p/d_i = 0.769$ and $e/d_i = 0.081$.

1. Introduction

Heat transfer in tube flow is widely used in different engineering applications like in energy process engineering, air conditioning or chemical industry. Miscellaneous techniques for heat transfer augmentation are described in the literature. These techniques are used to enhance the heat transfer, to reduce the size of heat exchangers, the pressure drop or the manufacturing costs. Webb et al. [1] classified the enhancement techniques into passive techniques (no external power required) and active techniques (external power required). Among the passive techniques rough surfaces are listed. Webb and Kim [2], for example, assigned wire coil inserts, dimpled tubes and corrugated tubes to rough surfaces.

Corrugated tubes are formed by a cold rolling process, leading to a helical corrugation of the tube wall. These corrugations cause disruptions of the boundary layer, which enhance the heat transfer and increase the friction factor. Corrugated tubes were studied by a lot of authors (e.g. [3–12]) with the background of different applications. Most of the previous studies only contain information about single-helix corrugation. Rainieri et al. [5] and Mac Nelly et al. [11,12] examined cross-corrugated tubes, where the helical corrugation was applied in opposite direction (see Fig. 1).

For single-helix corrugations and wire coil inserts, Li et al. [13] and Ravigururajan and Bergles [14] described a rotational flow along with the disruption of the boundary layer. Contrarily the fluid rotation in cross-corrugated tubes is suspended by the inversely oriented corrugations. This was proofed by Mac Nelly et al. [11], whose experimental and numerical studies showed that a single-helix corrugation induces a significant circumferential velocity, whereas the average circumferential velocity in a cross-sectional area of a cross-corrugated tube is equal to zero. Within this study, the cross-corrugated tube with a corrugation height of 0.7 mm and a corrugation angle of 19° showed a better performance than all other tested single-corrugated and cross-corrugated tubes.

Rainieri et al. [5] investigated three single-corrugated and two cross-corrugated tubes at low Reynolds numbers. They showed that the onset of turbulence in single-corrugated and cross-corrugated tubes is between $700 < \mathrm{Re} < 800$ and $500 < \mathrm{Re} < 600$, respectively. In addition, they reported a higher increase of the heat transfer and friction factor for cross-corrugated tubes than for single-corrugated tubes.

The objective of the present experimental study is to extend the studies of Mac Nelly et al. [11] and Rainieri et al. [5], who showed the high potential of cross-corrugated tubes. Additional investigations of the influence of different geometrical configurations on

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Nomenclature

A	surface area
A_c	cross-sectional area
a_i	parameter in fitting model
c_p	specific heat capacity at constant pressure
d	tube diameter
e	corrugation height
F	correction factor on Nu
f	Darcy–Weisbach friction factor
G	mass velocity
h	heat transfer coefficient
k	thermal conductivity
L	tube length
$\dot{m}$	mass flow rate
N	number of corrugation starts per perimeter
p	corrugation pitch
$\dot{Q}$	heat transfer rate
S	sensitivity
s	tube wall thickness
$\overline{T}$	bulk temperature
T	temperature
UA	overall heat transfer ability
v	specific volume

Greek symbols

Δ	difference
Δp	pressure drop
μ	fluid dynamic viscosity
ϕ	severity index
ρ	density
φ	corrugation angle

Subscripts

cp	constant fluid properties
i	inner side
in	at inlet conditions
lm	log-mean
o	outer side
out	at outlet conditions
s	smooth tube
W	tube wall
m	mean
max	maximum
min	minimum

Dimensionless numbers

Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number

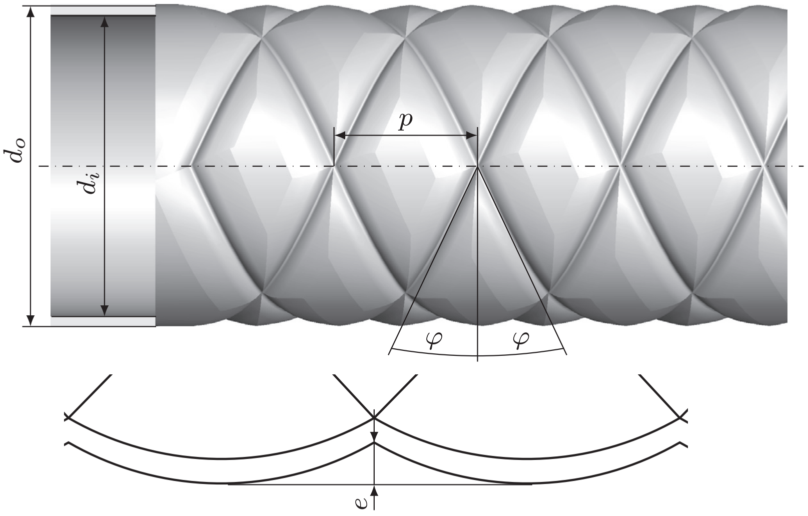

Fig. 1. Sketch of a cross-corrugated tube with its dimensions: inner and outer diameter d_i and d_o, corrugation angle φ, corrugation height e and corrugation pitch p.

heat transfer and friction are necessary to achieve the optimal configuration of the geometrical parameters of cross-corrugated tubes.

2. Tested tubes

In this study, heat transfer and friction characteristics of 18 different cross-corrugated tubes, listed in Table 1, are examined. The tubes were cross-corrugated by a cold forming process. The corrugations were made with a tool containing two sets with three rolls. The sets are rotating around the tube with opposite directions and angles. This leads to cross-corrugated tubes with three starts N per perimeter and direction. Fig. 1 shows a sketch of a cross-corrugated tube with its dimensions: inner and outer diameter d_i and d_o, corrugation height e, corrugation pitch p and corrugation angle φ. The inner diameter d_i of the cross-corrugated tube is the same as of the non-deformed smooth tube. Due to the manufacturing process, the tube pitch p depends on the values of N, d_o, e and φ as follows

$$p = \frac{\pi(d_o - 2e)}{N}\tan\varphi. \tag{1}$$

As regards single-helix corrugations some authors [10,15–17] use the severity index ϕ

$$\phi = \frac{e^2}{p\,d_i} \tag{2}$$

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