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Review

Numerical simulation of turbulent air flow on a single isolated finned tube module with periodic boundary conditions

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ABSTRACT

A helically segmented finned tube bank is simulated as a single isolated finned tube module in order to reduce computational domain in 99%. The numerical simulation is conducted with the Reynolds Averaged Navier–Stokes Equations (RANS) approach and the turbulence effect is modeled with the k–ε RNG model. The finned tube geometry is represented by means of cut-cell method, whereas the inside fluid temperature is considered by means of an average temperature. Periodic boundary conditions are implemented and, as a consequence, new terms in momentum and energy equations should be included to represent pressure drop and cooling air flow. Results show the effect of implementing periodic boundary conditions on turbulent kinetic energy, and its dissipation rate only is reflected on local properties in the zones of high flow interaction. Predictions are validated with experimental data and the best correlations available in the open literature. Results show good precision and the same tendency in the velocity field. The numerical-mean friction factor and Nusselt number present deviations of 0.67% and 2.98%, respectively. Therefore, an appropriate representation of turbulent flows is obtained and the numerical model can be applied to studies on heat exchangers at industrial scale.

1. Introduction

Helically segmented finned tubes are used in industrial applications in order to obtain compact heat recoveries. These apparatus are small because the gas phase turbulence and the heat transfer surface are increased by the presence of fins; both are relevant in heat transfer. However, the gas phase pressure drop is elevated and consequently, operational problems such as backpressure can emerge. Therefore, a detailed study focusing on the hydrodynamics over finned tubes is important in order to understand the fluid dynamics and heat transfer phenomena. There are tree methods of analysis; the first uses semi-empirical models, the second proposes experimental measurements, and the third uses Computational Fluid Dynamics (CFD) techniques. Semi-empirical models allow a quick evaluation of thermo-physical phenomena but only global analyses are obtained. Experimental methods represent the real phenomenon but the cost may be high. Computational Fluid Dynamics analyses provide complete and detailed information of interaction between flow hydrodynamics and heat transfer but require good computational support and long calculation time. However, the calculation time can be reduced by means of implementation of adequate boundary conditions.

In the open literature, there are several numerical studies on finned tubes (symmetric and asymmetric fins arrange). The majority of papers are restricted to symmetric finned tubes such as annular finned tubes. For example, Mon and Gross [1] studied numerically the effect of fin spacing on annular finned tube banks in staggered and in-line arrangements for turbulent air flow at Reynolds Numbers in the range of 8.6×10^3 to 4.3×10^4. The numerical model considered k–ε RNG turbulence model and symmetry boundary conditions in perpendicular directions to the streamwise. Predictions were compared with semi-empirical correlations for overall heat transfer and pressure drop; numerical results showed deviations of 15%. Meanwhile, Bilirgen et al. [2] analyzed the effects of fin spacing, fin height, fin thickness, and fin material on the overall heat transfer and pressure drop for a single row of finned tubes for Reynolds Numbers of 10,000–45,000. RNG k–ε turbulence model and symmetry boundary conditions were adopted in numerical simulations. The study was focused on heat transfer and only the mean Nusselt numbers were compared with semi-empirical correlations. Predictions were reasonably in

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Nomenclature

Symbols

A	surface area
A_2	tube row coefficient
c_p	specific heat at constant pressure
$D\phi$	dimensionless deltas
d	diameter
e	thickness
f	friction factor
G	gas mass flux
$G\phi$	dimensionless gradient
$\overrightarrow{g}$	gravitational acceleration
$\bar{h}$	average convective coefficient
$\tilde{h}$	mean enthalpy
$\tilde{J}_h$	conduction heat flux
K	dimensionless kinetic energy
k	thermal conductivity
$\tilde{k}$	turbulent kinetic energy
L	characteristic length
L_D	dimensionless position
l	height
$\dot{m}$	mass flow rate
Nr	number of tube rows
Nu	Nusselt Number
$\overline{Nu}$	average Nusselt number
$\tilde{P}$	periodic pressure
P	pressure
Pr	Prandtl number
Q	flow rate
$\dot{Q}$	heat addition
Re	Reynolds number
R_f	fouling factor
S	pitch
s	gap
$\tilde{T}$	periodic temperature
T	temperature
U	overall heat transfer coefficient
w_{in}	initial velocity
$\overrightarrow{\tilde{V}}$	instantaneous velocity
$\overrightarrow{V}''$	fluctuating velocity
z	streamwise spatial direction
$\Delta\tilde{P}$	pressure drop
ΔT_{ML}	logarithmic mean temperature difference
$\Delta\phi$	delta property
$\nabla\tilde{P}$	pressure gradient
$\nabla\tilde{T}$	temperature gradient

Greek letters

α	relaxation factor
β	average pressure gradient
$\bar{\rho}$	mean density
ρ	density
$\tilde{\varepsilon}$	turbulent dissipation rate
η	efficiency
μ	viscosity
γ	temperature gradient term
ϕ	property (pressure or temperature)

Subscripts

b	bulk, boundary, numerical-mean
f	fin
g	gases
l	longitudinal
o	outside (tube diameter), overall, desired
r	radiation, rows
t	bare tube, transverse
v	volume-equivalent diameter
w	wall, tube material

good agreement with the two sets of experimental data. On the other hand, there are studies of symmetric fins arrange that consider corrugated fins in cylindrical tubes as proposed Tao et al. [3], Karmo et al. [4] and plain fins in elliptical tubes as is presented by Sun and Zhang [5]. These papers considered symmetry boundary conditions in order to reduce computational domain and simulations were realized for turbulent air flow (Karmo et al. [4] and Sun and Zhang [5]) and laminar air flow (Tao et al. [3]). Predictions were compared with experimental data; results showed deviations less than of 4.7% for Nusselt number and less than 13.2% for friction factor for studies conducted by Tao et al. [3] and Sun and Zhang [5].

In the case of asymmetric finned tubes, the studies are focused in helically segmented finned tubes. For example, Hofmann and Ponweiser [6] conducted a three-dimensional simulation on a single helically segmented finned tube. The study was developed for turbulent air flow with Reynolds numbers from 4500 to 35,000. The numeric model considered Dirichlet boundary conditions and RNG k-ε turbulence model. Predictions were compared with semi-empirical correlations with a good agreement. Subsequently, Mcilwain [7] developed a comparison between single serrated finned tube and single plain finned tube. The simulation was performed for half of every finned tube with Dirichlet Boundary conditions at velocities of 1–5 m/s. Numerical results showed that serrated fins improve the heat transfer although the mechanism may not be as amenable to a straightforward treatment. Afterwards, Lemouedda et al. [8] developed a three-dimensional numerical simulation in a small finned tube bank with Dirichlet boundary conditions. Numerical simulations were realized for laminar air flow with Reynolds numbers of 600–2600. This study only compares numerical heat transfer from different fin geometries and results showed that an increase of the number of fin segments improved the performance of the serrated finned tubes. Finally, Hofmann and Walter [9] studied numerically the heat transfer and pressure drop in helically segmented finned tubes and helically plain finned tubes. Numerical simulations were performed for two half adjacent finned tubes and considered periodic boundary conditions (along the finned tube length) and symmetry conditions in transversal direction of flow and Dirichlet boundary conditions in the streamwise. The local and global averaged heat transfer and pressure drop was studied for turbulent air flow with Reynolds number from 3500 to 50,000. Results showed good agreement with experimental data within ±15% uncertainty.

Numerical simulations on asymmetric finned tubes (helically segmented finned tubes) have been performed for a single finned