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SRANS Simulation on a Helical-Segmented Finned Tube Bank

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***Abstract* - A numerical simulation on a six-row helical-segmented finned tube in a staggered layout is performed with the Reynolds Averaged Navier-Stokes (RANS) approach. The turbulence effect is represented with the k-ε RNG model, and a fixed temperature in each tube row considers the inside fluid temperature. The tube bank is represented by a small finned tube bank and a single interacted module. The small finned tube bank considers symmetry conditions on the sides of the computational domain. The single interacted module considers periodic boundary conditions for velocity, pressure, and temperature. Both simulations are compared to develop the basis of complex simulations such as repetitive finned tube modules. Average values on parallel planes to the streamwise direction for velocities, pressures, and temperatures are compared in both simulations. The comparative analyses show deviations lower than 11% for the velocity field, 12% for the pressure field, and 10% single for the temperature field. Therefore, results show an appropriate flow representation with periodic boundary conditions.**

Keywords: Numerical simulation, SRANS, Small finned tube bank, Single interacted module, Symmetry and periodic boundary conditions.

I. INTRODUCTION

A helical-segmented finned tube bank is used in heat recovery applications because it is small. Fins increase gas phase turbulence and heat transfer surface, but the pressure drop increases. In the open literature, many numerical works focus on helical-segmented finned tubes. Some studies developed numerical simulations on one or two halves of a helical finned tube, as studies performed by Hofmann & Ponweiser [1], Mcilwain [2], and Hofmann & Walter [3]. Other authors' simulated tube banks as small finned tube banks by implementations of symmetry boundary conditions. Simulations are performed on staggered or in-line layouts for laminar or turbulent flow. The hydrodynamics and heat transfer have been studied in works such as Lemouedda et al. [4], Kumar et al. [5], Martinez et al. [6, 7], Lindqvist & Næss [8],Zhou et al. [9], and Lang et al. [10]. Implementing periodic boundary conditions on a single interacted module is performed mainly on bare tubes, as simulations conducted by Benhamadouche & Laurence [11] and Salinas-Vázquez et al. [12]. The work carried out by Salinas-Vázquez et al. [13] analyzed the hydrodynamics of helical-segmented finned tubes on a single interacted module. Finally, simulations performed by Beale [14, 15] studied the heat transfer on a single interacted bare-tube module.

In the open literature, most works have simulated finned tube banks as small finned tube banks because the implementation of symmetry boundary conditions is less complex than periodic boundary conditions. The implementation of periodic boundary conditions on a single interacted module has been focused on hydrodynamics [11-13] due to difficulty in coupling the heating/cooling of external flow. Works proposed by Beale [14, 15] studied heat transfer in a single interacted bare-tube module. Therefore, this work conducted a numerical simulation in a steady state for turbulent flows under periodic and symmetry boundary conditions in a six-row helical-segmented finned tube in a staggered layout. The main objective is to compare numerical simulations on a small finned tube bank and a single interacted module for helical-segmented finned tubes. Then, symmetry boundary conditions are applied on a small finned tube bank, considered a benchmark case. Periodic boundary conditions are imposed on a single interacted module. Comparative analysis of both simulations allows us to get numerical criteria on heat transfer simulations with periodic boundary conditions.

II. CASE STUDY

A six-row helical-segmented finned tube in a staggered layout is represented by a Small Finned Tube Bank (SFTB) and a Single Interacted Module (SIM) to save computational resources. The SFTB considers the six tube rows and one finned tube (complete tube or two halves), as shown in Figure 1. The SIM only considers three tube rows and two finned tubes (one complete and four quarter tubes) in the fully developed zone, as shown in Figure 1. SFTB and SIM can adequately represent the physical phenomenon by correctly implementing boundary conditions (see section III). The work compares numerical predictions on both simulations at a uniform velocity of 1.5m/s and inlet temperature on the tube

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bank of 60°C. The geometric characteristics of the tube bank are presented in Table 1 and Figure 2.

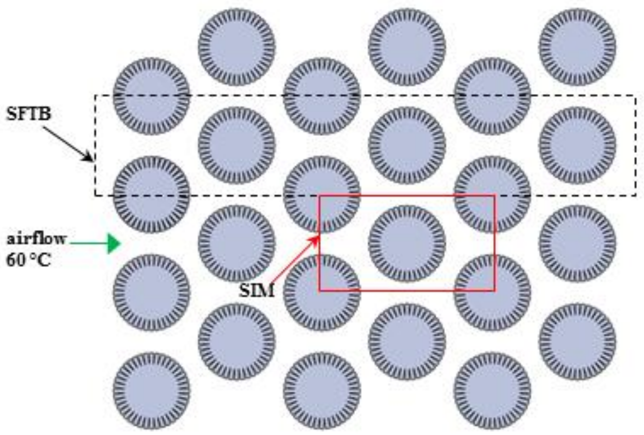

Figure 1: Representation of the tube bank

Table 1: Geometric characteristics of the tube bank

Tube dimensions (m)		**Fin dimensions (m)**	
D_o	0.0508	l_f	0.01905
D_i	0.044	l_s	0.01275
L_{tf}	1.0	t_f	0.0012
L_{tb}	0	s_f	0.003
L_{tube}	1.0	w_f	0.0048
Tube layout		d_f (fins/m)	236.0
S_t (m)	0.1143		
S_l (m)	0.09906		

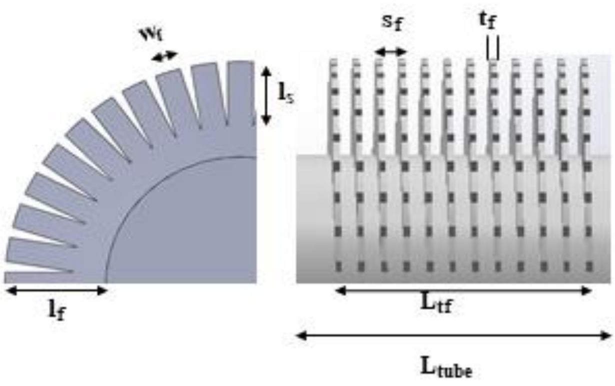

Figure 2: Geometric features of the finned tube

III. NUMERICAL SIMULATION

A six-row helical-segmented finned tube in a staggered layout is simulated to compare the representation of a tube bank by an SFTB and SIM. The geometric characteristic (S_t and S_l) of the finned tube layout is shown in Table 1. Then, the simulation is focused on the external flow (air) because the gas phase dominates the heat transfer. The heating of the internal fluid (water) is considered by the average temperature inside each finned-tube line, according to the methodology proposed by Martinez et al. [16]. Then, two simulations are developed for a SFTB (benchmark case) and SIM, as described in section II. The computational domain of the SFTB (continuous black box) and the SIM (dotted red box) is presented in Figure 3. Details of the computational domain and boundary conditions implemented in the simulations are described in sections 3.2 and 3.3. Results obtained in the SFTB are used as a benchmark case for comparison with SIM simulation with periodic boundary conditions.

3.1 Governing Equations

Simulation is focused on the external flow for a turbulent flow in a steady state. The equations of continuity, momentum, and energy for a turbulent flow are used in the work. These equations are represented as a mean term($\bar{\emptyset}$), and its fluctuation ($\emptyset'$) in a Reynolds Average.

$$\nabla \cdot \left(\rho\bar{\vec{V}}\right) = 0 \tag{1}$$

$$\nabla \cdot \left(\rho\bar{\vec{V}} \otimes \bar{\vec{V}}\right) = -\nabla \cdot \bar{\vec{P}} + \mu\nabla^2\bar{\vec{V}} - \nabla \cdot \left(\rho\overline{\vec{V}'\vec{V}'}\right) + \rho\bar{\vec{g}} \tag{2}$$

$$\nabla \cdot \left(\rho\bar{\vec{V}}\bar{h}\right) = -\nabla \cdot \bar{\vec{J}}_h - \nabla \cdot \left(\rho\overline{\vec{V}'h'}\right) \tag{3}$$

Where ρ, $\mu\bar{\vec{V}}$, $\vec{V}'$, and $\bar{h}$ are the density, viscosity, mean velocity, fluctuating velocity, and mean enthalpy, respectively. The terms $\otimes$, $\rho\overline{\vec{V}'\vec{V}'}$, $\rho\overline{\vec{V}'h'}$, $\bar{\vec{J}}_h$, and $\bar{\vec{P}}$ are the dyadic product, the Reynolds stress tensor, the turbulent heat flux, the conduction heat flux, and the pressure tensor, respectively.

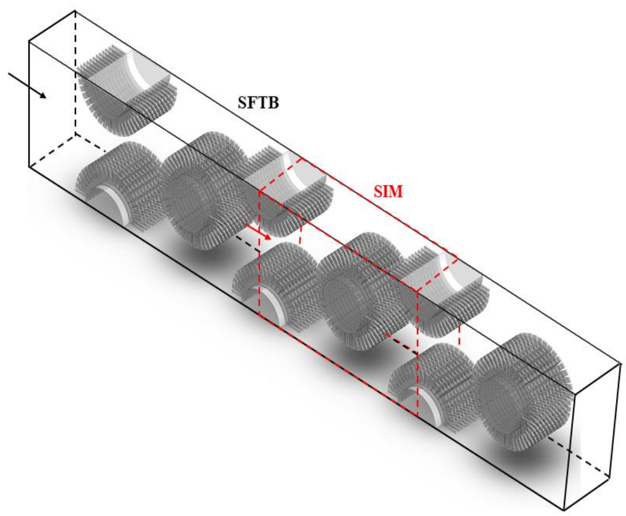

Figure 3: Computational domain of the SFTB and SIM

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The Reynolds stress tensor is closed with the turbulence model k-ε RNG (Renormalization Group). The SST k-ω model uses the k-ω model near walls and k-ε in the zones of free flow (area away from the walls). The turbulent heat flux vector is modeled by a turbulent flow viscosity through an analogy between momentum transfer and thermal energy transfer. The transport equations for momentum and energy are solved with the finite volume method in steady-fully developed flow with the Computational Fluid Dynamics (CFD) code PHOENICS.

3.2 Boundary Conditions

The SFTB imposes symmetry boundary conditions on the sides of the computational domain, as shown in Figure 1. Symmetry Boundary Conditions (SBC) propose slip walls in the stream wise direction, zero normal velocities, and zero normal gradients of all variables at the symmetry plane. These boundary conditions have been used in helical-fin tube banks with satisfactory results, as Lemouedda et al. [4] and Martínez-Espinosa et al. [6]. PBC saves computational resources because the computational domain is reduced considerably to a SIM, as shown in Figure 1. Then, a SIM requires a position in the fully developed flow region because PBC periodic conditions assume infinite lengths, implying no influence of the walls or position in any of the directions. Then, a correct implementation of these boundary conditions is required to represent the physical phenomenon. This work considers the method focused on laminar flows by Patankar et al. [17] and Kelkar & Patankar [18].

3.3 Numerical Details

The computational domain used for the SFTB (Figure 1) is 0.59874 m x 0.05194 m x 0.1143 m, whereas the SIM (figure 1) is 0.20312 m x 0.05194 x 0.1143 m. The mesh used on the SFTB (figure 1) contains 540000 cells, and the SIM has 182280 cells. The thermodynamic conditions used in this work are air uniform velocity of 1.5 m/s (Re_0=9652) kg/s and temperature of 60 °C, as shown in figure 1. The complex geometry was represented by Cartesian grids through cut-cell method [15]. Numerical simulations consider staggered grids under a hybrid discretization scheme in the convective term. The system operates ina stationary state, which is only exposed to one gravitational field, and gas discharge (outlet of the computational domain) occurs at sea-level atmosphere. Finally, the geometric characteristics of finned tubes are shown in Table 1 and Figure 2.

IV. RESULTS AND DISCUSSION

Numerical velocity, pressure, and temperature results for the SFTB and SIM are compared in the fully developed zone (see dotted red box in Figure 3). All figures compare the contours on the XZ plane at the same position. Furthermore, average values of properties in the stream wise direction are graphed in parallel planes (XY plane)every 5 mm. Then, Figure 4 shows the velocity contours (Figure 4a) and the average velocities comparison (Figure 4b) for the SFTB and SIM. Velocity contours show the typical flow behavior around finned tubes, such as the formation of recirculation zones at the rear area of the tubes and velocity bands on the side of the finned tubes. Average velocities show differences lower than 5% between SFTB and SIM, with maximum deviations of 11%. Therefore, numerical velocities show good agreement of predictions with periodic boundary conditions.

Figure 5 presents both cases' pressure contours (Figure 5a) and the average velocities comparison (Figure 5b). A typical phenomenon in turbulent flows around cylinders is observed in both contours. For instance, predictions reveal a high-pressure zone at the front area of the tubes by flow stopping abruptly and a recirculation zone at the rear part of the finned tube. Furthermore, a low-pressure area exhibits a stratified behavior at the module outlet. In the case of average pressures, the graph shows that predictions with periodic boundary conditions are close to results with the SFTB. Most deviations are lower than 5% and only a few values have deviations lower than 12%.

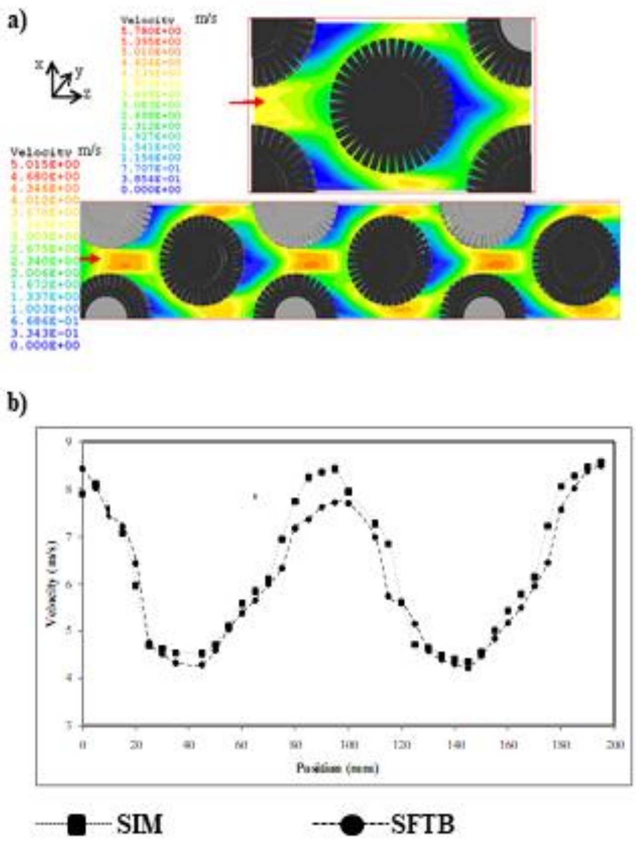

Figure 4: Velocity results

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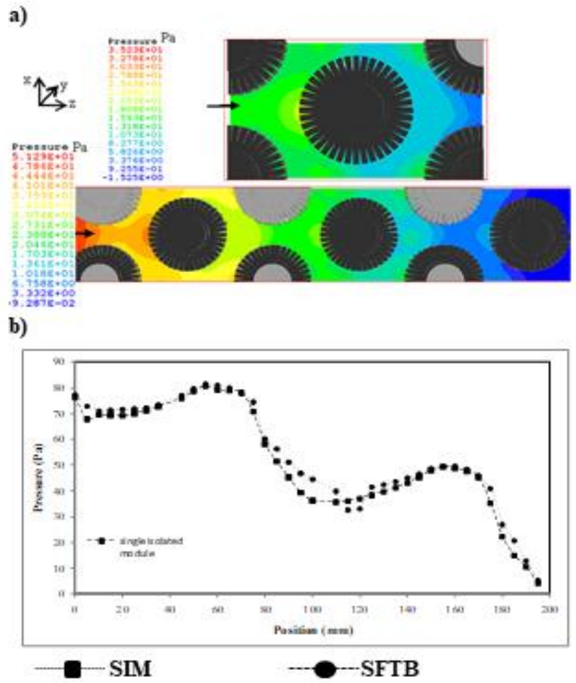

Figure 5: Pressure results

Figure 6 shows temperature contours (Figure 6a) and the average temperature values (Figure 6b) for both cases. Contours show a low-temperature area at the rear part of the finned tubes, and the most important heat transfer effects occur at the front and the sides of the finned tubes. Furthermore, temperature contours show apparent discrepancies in the numerical results. However, this happens because simulation at the SFTB is conducted with airflow at 60 °C, whereas the airflow temperature in the SIM is 53 °C. After all, the flow is cooling by the first two rows. Finally, temperature results show that most deviations are lower than 4%, and only five results present maximum deviations of 10%. Therefore, predictions with SIM are very close to SFTB.

The turbulent kinetic energy (KE) and turbulent dissipation rate (EP) between SFTB and SIM are not compared because periodic boundary conditions were only considered on the velocity, pressure, and temperature. KE and EP are presented for the SFTB (benchmark case). Then Figure 7 shows the turbulent kinetic energy and the turbulent dissipation rate. This figure presents a periodic behavior in the KE and EP that requires implementing a periodic boundary condition in future simulations. The turbulent kinetic energy shows maximum values in the entire front region of the finned tube and at its sides. This implies these regions have the strongest dissipative effects and high flow turbulence. The dissipation rate exhibits a slightly asymmetric behavior, as the other variables. Therefore, an adjustment of the methodology proposed by Patankar et al. [17] and Kelkar &Patankar [18] is established by inserting KE and EP as periodic variables.

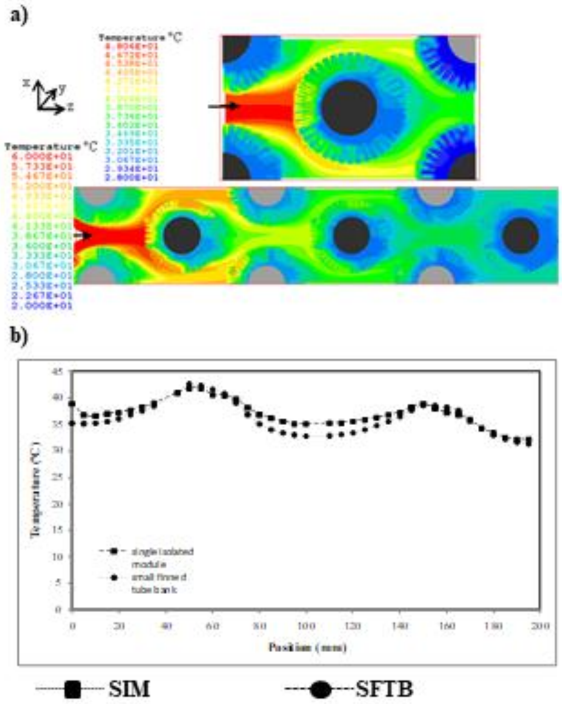

Figure 6: Temperature results

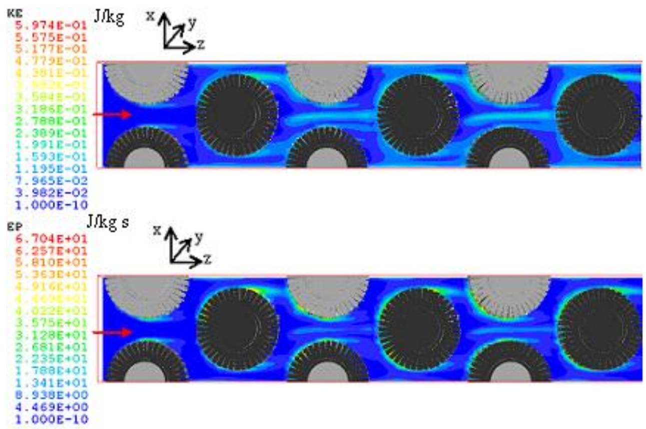

Figure 7: turbulent kinetic energy and turbulent dissipation rate contours

V. CONCLUSION

The Numerical comparison between SFTB and SIM shows similar velocity, pressure, and temperature behavior. Results reveal deviations less than 11%, 12%, and 10% for velocity, pressure, and temperature, respectively. Furthermore, most of the results have deviations less than 5%. Then, the hydrodynamics and heat transfer with PBC are adequately represented for the application of compact heat recoveries. Despite promising results in the SIM, predictions on the SFTB show that the turbulent kinetic energy and turbulent dissipation rate have a periodic behavior. Then, numerical simulations for a SIM require the implementation of PBC for the turbulent kinetic energy and turbulent dissipation rate.

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