International Journal of Thermal Sciences 134 (2018) 208–215

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Heat transfer and turbulent mixing characterization in screen-type static mixers☆

Charbel Habchi[a,*], Fouad Azizi[b]

[a] Notre Dame University - Louaize, Thermofluids Research Group, P.O. Box: 72, Zouk Mikael, Zouk Mosbeh, Lebanon
[b] American University of Beirut, Chemical Engineering Department, P.O. Box: 11-0236, Riad El Solh, Beirut, Lebanon

ARTICLE INFO

Keywords:
Turbulent mixing
Static mixer
Nusselt number
Convection

ABSTRACT

A numerical investigation of one phase flow through tubular pipes equipped with screen mixers was undertaken to study their effect on turbulent mixing as well as their heat transfer performance. The current work investigates 2D simulations in order to get insight on transport phenomena parameters in these mixers. Micromixing time was found to be enhanced by the use of screens with smaller fraction open areas because of their consequent effect on the local variation of the turbulence energy dissipation rate. Moreover, heat transfer experiments also showed that the Nusselt number, which increases with $Re^{0.68}$ independently of the screen geometry, is also inversely proportional to the fraction open area of the screen. When compared with published data, screen mixers showed that their heat transfer performance compare favorably with the performance of various commercially available static mixers.

1. Introduction

The growing interest in the use of tubular reactors equipped with static mixers, over conventional mixers, emanates from their inherent advantages whereby better performance can be achieved at lower capital and operating costs. Findings in the literature highlight the higher multiphase mass transfer and reaction rates that could be achieved in energy efficient manners while simultaneously handling large flow rates and achieving high heat removal/addition rates [1–7]. Furthermore, the insertion of properly-selected static mixing elements into tubular reactors allows for the introduction of the various reactants at different points along the reactor length, thereby facilitating the achievement of optimal temperature and reactant concentration profiles that are required to achieve optimal selectivity and conversion [8–13].

Tubular contactors/reactors equipped with screen-type static mixers have been successfully employed in achieving high rates of mass transfer at moderate energy expenditures. This type of static mixers have been used to repetitively superimpose an adjustable, radially-uniform, highly-turbulent field on the nearly plug flow conditions encountered in high velocity pipe flows. Screens have long been used to modify fluid motion for the production or reduction of turbulence scales and intensity, and to remove or create mean velocity non-uniformities [14]. The very high energy dissipation rates present in the thin region adjacent to the screen are particularly effective in processing multiphase systems. This not only helps in the formation of fine dispersed phase entities (bubbles and/or drops) but also considerably enhances the value of the interphase mass transfer coefficient [6,15–17]. In addition, the quasi-isotropic turbulence generated by grids was taken advantage of to study the effect of turbulent mixing on the evolution of chemical reactions [18] and served as a medium for testing the applicability of micromixing models [19].

The ability of screen-type static mixers to promote contact between different phases was found to be about 5-fold more energy efficient than mechanically agitated tanks equipped with Rushton-type impellers [20]. Furthermore, interfacial areas as high as 2200 m^2/m^3 could be efficiently generated in the case of gas-liquid systems [21,22], while oxygen transfer efficiencies as high as 4.2 kg/kWh were achieved even in the presence of surfactants [15]. For the case of liquid-liquid dispersions, volumetric mass transfer coefficients, $k_L a$, as high as 13 s^{-1} were attained and enabled for 99% of the equilibrium conditions to be achieved in less than 1 s [16]. Such good performance, which is attributed to not only the formation of very fine dispersed phase entities but also enhanced mass transfer coefficients, is credited to the very high grid-generated turbulence and the consequent elevated micro-mixing intensities generated in the regions adjacent to the screens [6,19].

☆ This work was presented at Eurotherm Seminar 106 "Physical and chemical phenomena in heat exchanger and multifunctional reactor for sustainable technology", October 10–11 2016, Paris, France.

* Corresponding author.
E-mail address: charbel.habchi@ndu.edu.lb (C. Habchi).

https://doi.org/10.1016/j.ijthermalsci.2018.08.016
Received 5 January 2018; Received in revised form 27 July 2018; Accepted 6 August 2018
1290-0729/

Furthermore, these characteristics offer the flexibility of designing the reactor to meet various mixing and/or energy requirements where the mass transfer efficiency can be easily adjusted according to the requirements of the reaction. For example, whereas a short inter-screen spacing favors the production of fine dispersions that are typical of high mass transfer rates and fast reactions, a longer spacing would be favorable for conditions of slow reactions and/or low energy requirements. However, any change in the reactor configuration and/or operating conditions will impact its performance.

Preliminary investigations [19,21,23] suggest that a very rapid decay of the turbulent energy dissipation takes place in the very thin layers located immediately after the screen, and that bubble/drop breakup is therefore expected to dominate in this high-energy dissipation region. On the other hand, coalescence becomes significant further downstream where low turbulent energy dissipation rates prevail. These findings highlight the importance of accurately determining the spatial variation of the energy dissipation rate if the simulation results of multiphase flows are to bear a close resemblance to those actually occurring [22,24].

In a previous study, Azizi and Al Taweel [3] presented a one dimensional approach for modeling the spatial variation of the energy dissipation rate behind a screen. In it, the use of the homogeneous and isotropic turbulence decay equation was extended to the anisotropic region. Their proposed turbulence decay profile behind a grid was divided into two regions, a region of constant high energy dissipation rate prevalent over a certain distance downstream of the grid, and a region of fast decay where the homogenous isotropic turbulence decay equation applies. Using this representation for modeling the spatial variation of the energy dissipation rate, all energy sources for the flow through screens were accounted for and the calculated values matched the experimentally determined volume average ε data quite well.

The accuracy of this approach can be enhanced by performing CFD simulations of the flow through this type of reactor/contactor. This would help in better detailing the hydrodynamics and discussing its mixing characteristics from heat and mass transfer perspectives. Consequently, this paper presents a CFD study of flow through screen-type static mixers. It will present the outcome of 2D simulations dealing with the hydrodynamic and heat transfer characteristics of the flow and will investigate the effect of changing the screen geometry and/or operating conditions on the pressure drop, spatial variation of the energy dissipation, micromixing time as well as the Nusselt number in heat transfer operations. New correlations for the Nusselt number and friction coefficient are also reported.

2. Computational domain

The computational domain consists of a circular pipe of inner diameter, $D = 25.4$ mm, and a total length of 560 mm, in which seven screens are inserted at an inter-screen distance $h = 70$ mm. Taking advantage of the axisymmetric flow configuration, the domain is reduced to a two-dimensional axisymmetric one as schematically shown in Fig. 1.

Screens are generally characterized by their mesh size, M, wire/bar size, b, and the fractional open area, α. Three different screen geometries are studied depending on their dimensions as shown in Table 1. In addition, the mean flow velocity was changed between 0.5 and 2 m/s. The full range of operating conditions used in the present study is summarized in Table 2, namely the value of the pipe and wire Reynolds numbers, Re_D and Re_b, respectively, are shown for the various conditions.

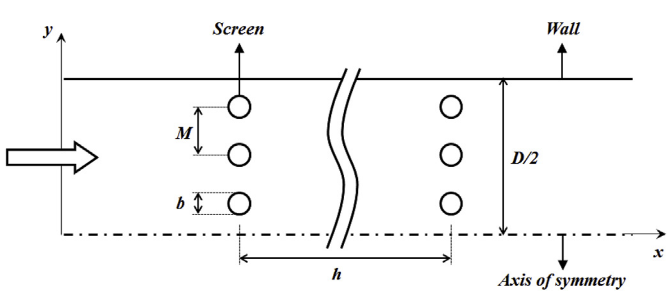

Fig. 1. Computational domain and dimensions.

Table 1
Screen types and dimensions.

Screen type	Wire diameter, b (mm)	Mesh size, M (mm)	Opening ratio, α (%)
I	0.508	1.058	27
II	0.152	0.362	33
III	0.305	0.845	41

Table 2
Operating conditions.

Pipe Reynolds number Re_D	Mean flow velocity U_m (m/s)	Wire Reynolds number, Re_b		
		Screen I	Screen II	Screen III
12,640	0.5	254	76	153
25,278	1	508	152	305
37,918	1.5	762	228	458
50,557	2	1016	304	610

A non-uniform unstructured hybrid mesh was performed. Special attention was paid to the near-wall refinement of all solid boundaries (wall and screen surfaces) so as to take into account the high gradients in these regions and to insure that the dimensionless wall distance y^+ values stay as close to 1 as possible. An example of the refined mesh is presented in Fig. 2 for screen type III.

Furthermore, a grid independence study to determine the appropriate mesh density was performed, in which, the solver was run with increasing densities until no significant effect on the results was detected. Local adaptive mesh refinement was used where the cells are refined in regions with high velocity, temperature and turbulence

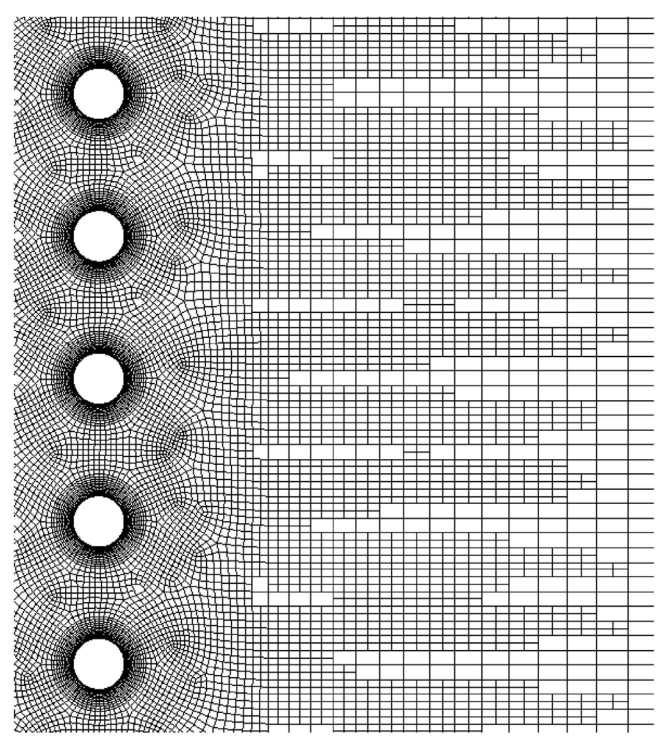

Fig. 2. Local mesh refinement.