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Research paper

Thermal mixing enhancement of a free cooling/heating system with a 2D space-filling plate

An Liang Teh [a, 1], Yong Hoi Siow [a, 1], Wai Meng Chin [b], Chee Ming Chia [c], Ji Jinn Foo [a, *]

[a] School of Engineering, Monash University Malaysia, 46150 Bandar Sunway, Malaysia
[b] O.Y.L. R&D Centre Sdn Bhd, 47000 Sungai Buloh, Selangor, Malaysia
[c] Faculty of Engineering and the Built Environment, SEGi University, 47810 Petaling Jaya, Malaysia

HIGHLIGHTS

- 2D planar space-filling inserts of various configurations were investigated.
- Effects of plate tilting performance at −45°, 0°, and 45° were numerically studied.
- Thermal mixing performance of tilted insert outperforms the non-tilted counterpart.
- Circular orifice generated flow fluctuations permit widest range of thermal mixing.
- Manufacturing sustainability could be secured with the use of circular orifice.

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ABSTRACT

Free-cooling/heating system has been incorporated with heating, ventilating and air-conditioning (HVAC) systems to provide low-cost cooling. The present work investigates numerically with the use of 2D space-filling plates to enhance the thermal mixing between the drawn in surrounding cooler air and the recycled warm air within a *T*-duct to strengthen the heat transfer at HVAC heat exchanger. Three inserts are used to generate turbulence at $Re_h = 2.19 \times 10^4$, i.e. positive square-fractal grid (PSFG), negative square-fractal grid (NSFG), and circular orifice (CO). Two-equation turbulence model is employed for turbulence kinetic energy κ predictions in insert induced thermal mixing. In particular, the effects of κ on space-filling geometry and tilted angle for each insert are discussed. Results show that for 45° tilted inserts, the thermal mixing performance of CO is about 2134%, 1382%, and 374% higher than the empty channel, PSFG, and NSFG, respectively, at $x/H = 4.2$. Tilted inserts thermal mixing are significantly better than the non-tilted cases. Plate tilting allows the production of larger scales of flow recirculation, of which accompany by higher flow fluctuations leeward from each insert. Therefore, with CO inserts being fully encompassed by the larger and wider scales of κ, the thermal mixing outperforms the space-filling fractal inserts.

1. Introduction

The rapid dwindling of fossil fuels has driven numerous attentions on the development of long-term sustainable and renewable energy in order to reduce the negative impact of pollution on human health and to promote efficient utilization of energy. In the contemplation of attaining an environmental benign atmosphere with lower carbon footprint, energy saving through the recovery from various unwanted waste heat or low temperature energy sources from industries, data centers, residential houses, or even electronics devices have been introduced [1–4]. It was widely recorded that the energy consumption of applying building heating, ventilating and air-conditioning (HVAC) systems account for approximately 50% of the total energy in buildings. However, with effective recycling of the exhaust air stream to precondition the drawn in surrounding air, either in the winter or summer, allows 60% of energy saving for the hybrid system [5]. Clearly, HVAC heat exchanger heat transfer coefficient could be enhanced by strengthening the turbulent and thermal mixing performance at the economizer. One of the most common solutions is to employ

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[*] Corresponding author.
E-mail address: Foo.Ji.Jinn@monash.edu (J.J. Foo).
[1] The authors contributed equally to this work.

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insert that placed in a *T*-duct at a certain distance apart after two air streams of different temperatures meet.

Insert with 2D planar regular grid or biplane square grid generated turbulence is approximately homogeneous and isotropic; the understanding of induced turbulent fluctuations and its decay of such least complicated configuration enables the development of turbulence theories [6–8]. Murzyn and Bélorgey [9] conducted an experimental study on 2D regular space-filling square grid along a free flow surface to investigate the basic characteristic of turbulence. They observed that the turbulent intensity increases significantly immediately leeward from the grid, followed by a rapid decay to a constant at about 15 times of the mesh size distance. It is interesting to note that the downstream fluctuations remain at 25% higher than the non-disturbed flow. In addition, Suzuki et al. [10] employed Direct Numerical Simulation (DNS) to study the fundamental statistics of turbulence generated by the regular square mesh. Their results showed that the turbulent fluctuation is anisotropic of about 17%. Nagata et al. conducted numerically the thermal mixing induced by various 2D space-filling planar regular grids between two parallel fluid flows of different temperatures using DNS. They reported that the conventional biplane square grid is able to generate a substantial thermal mixing along the interface at $Pr = 0.71$ and 7.1 [11]. Although biplane square grid is able to provide effective turbulent mixing of the passive scalar, the generated turbulence length scales are far smaller than the channel hydraulic diameter. Therefore, thermal mixing of the entire channel downstream from the insert remains limited [12].

To date, the concept of fractals is enjoying considerable popularity in strengthening the heat transfer coefficient in various applications [13,14]. Fractal grid is a configuration constructed based on a specific geometry that repeats itself and diminishes in size to form a complex pattern of different iterations [15,16]. Such feature opens up a wide range of unprecedented possibility in generating turbulence [17]. Several investigators have reported on the effects of fractal induced turbulence. Laizet and Vassilicos numerically shown that fractal grid of number of iteration $N = 3$, produces higher vorticities and turbulence intensities than the regular grid, the former hydrodynamic fluctuations progressively amplified immediately in the lee from the fractal geometry, and started to decay once it reaches the peak turbulence intensity level [18]. More importantly, it is also found that the fractal grid of $N = 3$ possesses a much wider coverage of high turbulence intensity level downstream from the insert. Seoud and Vassilicos experimentally investigated the details of fractal generated turbulence dissipation and decay with higher number of iteration, i.e. $N = 4$ using 2D planar space-filling fractal square grids. It was shown that fractals are capable in producing high Re_λ based on higher turbulence intensities produced. Interestingly, the Re_λ is at most three times higher than the traditional grids of significantly larger blockage ratio σ, with the same mean inlet velocity and wind tunnel [19]. Such increase in turbulence generation have been verified experimentally by Hurst and Vassilicos, Mazellier and Vassilicos, Nagata et al., and Nicolleau et al. in their respective research investigations [17,20–22]. Verbeek et al. employed multi-scaled circular cropped fractal grid of $N = 3$ on a low-swirl burner. They reported that turbulence and combustion rate are sensitive toward the level of fractality. The generated turbulence intensified when compared with the control single-scale grid [23]. Suzuki et al. numerically studied the thermal mixing performance of regular grid and $N = 4$ fractal square grid at $Re_M = 2500$ and $Pr = 0.71$, with flow streams of different temperatures, which are being channeled through the upper and bottom regions of the computational domain. The results recorded a considerably wider mixing layer along the interface downstream of the channel via space-filling fractal square grid [12]. Clearly, fractal generated long term coherent structures of different dynamics coupled with the smaller scaling in turbulent velocity fluctuations leeward from the 2D planar grid may lead to effective thermal mixing.

Other than 2D planar grids, orifice plate had been widely used in flow velocimetry and to generate wake turbulence. Shaaban numerically optimized the pressure coefficient of an orifice meter by installing a ring downstream of the insert. They aim to reduce the interaction between the main stream and the surrounding flow

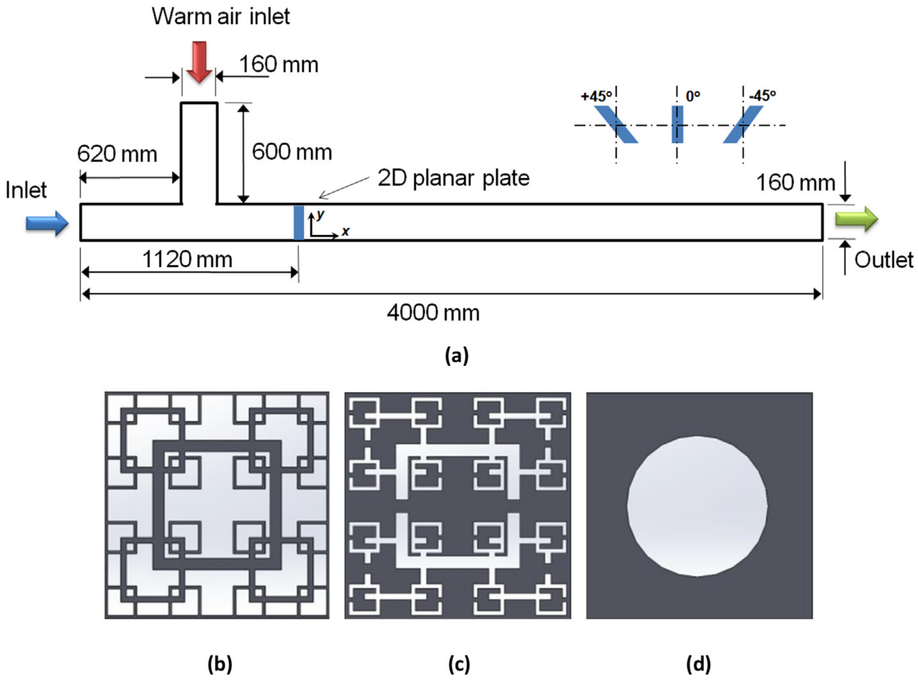

Fig. 1. Schematic of the (a) computational domain, (b) positive square fractal grid (PSFG), (b) negative square fractal grid (NSFG), and (c) circular orifice (CO).