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Thermal mixing enhancement of a free-cooling system with a fractal orifice plate

An Liang Teh[a,1], Kee Wen Chin[a,1], Eng Khim Teh[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

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ABSTRACT

The downstream hydrodynamic and thermal mixing performance of control and fractal orifice plates is numerically investigated. Each insert is positioned following a *T*-duct. Four blockage ratio plates $\sigma = 0.5$, namely, square orifice (SO), circular orifice (CO), square fractal orifice (SFO), and the Koch snowflake orifice (KSFO), are employed to promote thermal mixing. In particular, orifice configuration effects that induced transverse and horizontal thermal convergence, turbulence kinetic energy, and pressure gradient changes are discussed. Numerical validations reveal good agreement between the experimental and numerical results for centerline velocity and temperature distributions along the channel. The results show that KSFO outperforms the rest with respect to effective hydrodynamic and thermal mixing. It is critical to note that the maximum cross-sectional temperature difference $\Delta\theta$ for KSFO is the lowest and decreases further downstream. Clearly, such low $\Delta\theta$ values along the channel ensure temperature uniformity. Furthermore, KSFO generated area-averaged turbulence kinetic energy levels approximately 37%, 48%, 371%, and 1454% higher than those of CO, SO, SFO, and the smooth channel without an insert, respectively, at $x/H = 1.04$. It is also important to note that the studied fractal orifice pressure gradients are lower than those of CO and SO. These pressure drop observations are consistent with those of Nicolleau et al. (2011). Overall, the complex KSFO geometry forms a prominent balance between the pressure coefficient and thermal mixing at a Reynolds number of $Re_h = 1.94 \times 10^4$. Most importantly, this finding may help guide the long-term sustainable development of heating, ventilation and free-cooling air conditioning systems.

1. Introduction

A total of 5.6vTW of energy was consumed industrially in 2010, and this value is projected to increase by 56% over the next 30 years (U.S. Energy Information Administration, 2013). To effectively curb natural resource depletion, heating, ventilation and air conditioning (HVAC) systems with economizers have been proposed. The unwanted heat generated by HVAC systems is redrawn, premixed with the cooler surrounding air, and then recycled within a rectangular duct (Shehabi et al., 2010). This arrangement has been proven to significantly reduce daily electricity demand levels, thus reducing cooling costs (Shehabi et al., 2010; Siriwardana et al., 2013). HVAC systems can be made more efficient by improving the heat exchanger heat transfer coefficient or by regenerating waste energy. The latter involves effectively maximizing thermal mixing performance

* *Corresponding author*. Tel.: +60 3 55146255.
E-mail address: Foo.Ji.Jinn@monash.edu (J.J. Foo).
[1] These authors contributed equally to this work.
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Nomenclature

A	orifice blockage area, m^2
A_d	cross-sectional duct area, m^2
c_p	specific heat capacity, J/(kg K)
D	circular pipe inner diameter, m
D_{eq}	equivalent diameter, m
D_h	hydraulic diameter, m
H	channel height, m
N	number of fractal iterations
ΔP	pressure drop, Pa
P_d	duct perimeter, m
P_{in}	pressure before orifice, Pa
P_{out}	pressure after orifice, Pa
Re_h	Reynolds number scaled by the hydraulic diameter
Re_λ	Reynolds number scaled by the Taylor microscale
T	temperature, °C
$T_{A,ave}$	area-averaged temperature, °C
$T_{A,max}$	cross-sectional maximum temperature, °C
$T_{A,min}$	cross-sectional minimum temperature, °C
T_H	vertical inlet temperature, °C
T_C	horizontal inlet temperature, °C
u'	velocity fluctuations in x, m/s
U	velocity, m/s
U_c	normalized centerline air velocity
U_C	inlet ambient air velocity, m/s
v'	velocity fluctuations in y, m/s
$\vec{v}$	velocity vector, m/s
w'	velocity fluctuations in z, m/s
W	channel width, m

Greek symbols

σ	blockage ratio
λ	Taylor microscale, m
κ	Turbulence kinetic energy, J/kg
$\vec{\kappa}$	area-averaged turbulence kinetic energy, J/kg
ρ	air density, kg/m^3
μ	air viscosity, kg/(m s)
θ	normalized area-averaged temperature
θ_c	normalized centerline air temperature
$\Delta\theta$	maximum cross-sectional temperature difference
Θ	thermal mixing performance
$\bar{\Theta}$	average thermal mixing performance
η	system performance

levels while also minimizing pressure drop across the *T*-duct. Typically, inserts are added to a *T*-channel at a certain distance apart after two air streams of different temperatures meet.

Turbulence generated by a typical insert, namely a regular grid or so-called biplane square grid, is largely homogeneous and isotropic. The least complex configurations are supported by turbulence theories, which mainly focus on induced turbulence undulations and their decay (Comte-Bellot and Corrsin, 1966; Venkataramani and Chevray, 1978; Antonia et al., 2013). Overtime, more advanced techniques have been developed due to demands for stronger turbulent fluid flow fluctuations and thermal and chemical mixing mechanisms to cater to industrial needs. Thus, fractal geometry approaches to turbulent flow production have been formulated (Laizet and Vassilicos, 2011, 2012). A fractal grid is a configuration of a specific geometry that repeats and diminishes in size, thus forming patterns of various iterations (Mandelbrot, 2006; Kochergin and Kearney, 2006). Such features create unprecedented opportunities for turbulence generation.

Several researchers have reported on effects of fractal-induced turbulence. Mazzi and Vassilicos (2004) used a fractal-forcing model to conduct direct numerical simulations (DNS) of stationary, homogenous and isotropic turbulent flows. The authors concluded that at relatively low Reynolds numbers, fractal forced turbulence shows properties that only arise in turbulence forced at large scales and at predominantly higher Reynolds numbers. Seoud and Vassilicos (2007) studied the dissipation and decay of fractal-generated turbulence using space-filling fractal square grids. It was shown that fractals can produce high local Taylor microscale (λ) Reynolds numbers Re_λ, whereby corresponding turbulence intensities generated are at most 3× higher than classical grids of significantly higher σ. These intensified turbulence generation patterns were experimentally confirmed by Hurst and Vassilicos (2007), Mazzellier and Vassilicos (2010), Nagata et al. (2013), and Nicolleau (2013). Valente and Vassilicos (2011) employed a similar wind tunnel to that used by Mazzellier and Vassilicos (2010) to examine turbulence decay induced by a space-filling fractal grid. It was found that the flow field leeward from the fractal grid is highly inhomogeneous; the inhomogeneity of such flow fluctuations vastly decreases when a peak turbulence intensity level is reached. It is important to note that inhomogeneous turbulence is desirable, as this ensures effective thermal mixing downstream. Clearly, this effect is not limited to two-dimensional (2D) fractals. Hiramatsu et al. (2011) employed a Sierpinski tetrahedron, a three-dimensional (3D) configuration with a fractal dimension of two, to study corresponding wake generation patterns. It was found that despite the small scale of the wind tunnel, fractal geometries can generate relatively high Re_λ values, primarily due to an increase in turbulence intensity levels. Thus, the unique capacities of fractals in inducing higher fluid flow fluctuations may prove useful when applied to other scalar fields, e.g., for heat and mass transfer.

Currently, airside free-cooling systems or economizers can help reduce HVAC cooling system power consumption (Rackes and Waring, 2014). It was reported that when optimized strategies are employed, an indirect airside free-cooling system can save up to 29% of yearly energy (Zhang et al., 2014). To improve the free-cooling premixed process carried out before the working fluid reaches the heat exchanger, Siao (2014) experimentally compared the thermal mixing performance of a space-filling fractal square grid of three iterations with a circular orifice. Each insert was tested at a fixed distance from a Tee. It was found that the latter outperforms the former with respect to thermal mixing due to a higher level of hydrodynamic recirculation leeward from the orifice. However, employing a circular orifice significantly increase the pressure coefficient. Shaaban (2014) numerically optimized the orifice meter pressure drop by installing a ring in the downstream area of the orifice to limit eddy intensity levels and interactions between the main stream and the surrounding recirculation in the downstream area of the orifice meter. A 31–33% pressure loss reduction was reported. Aly et al. (2010) studied pressure drop and recovery patterns in downstream areas of von Koch fractal-shaped orifices in a circular channel. These trends were compared with those found in regular circular orifices of the same area. It was concluded that fractal orifice pressure drop