Applied Energy 184 (2016) 531–547

Contents lists available at ScienceDirect

Applied Energy

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

Numerical investigation of the temporal evolution of particulate fouling in metal foams for air-cooled heat exchangers

Sahan Trushad Wickramasooriya Kuruneru, Emilie Sauret *, Suvash Chandra Saha, YuanTong Gu

Laboratory for Advanced Modelling and Simulation in Engineering and Science, School of Chemistry, Physics & Mechanical Engineering, Queensland University of Technology, Brisbane, QLD 4001, Australia

HIGHLIGHTS

- A numerical method to investigate particulate fouling in metal foams is developed.
- A Weaire-Phelan model is proposed as an alternative to a real metal foam model.
- Fouling mechanisms vary depending on foulant properties and boundary conditions.
- Foulant residence time and mathematical relations to assess fouling are proposed.

ARTICLE INFO

Article history:
Received 9 May 2016
Received in revised form 5 October 2016
Accepted 16 October 2016

Keywords:
Metal foam
Particulate fouling
Air cooled heat exchanger

ABSTRACT

Metal foams have gained popularity in the renewable energy industry due to their superior thermo-physical properties. In the present study, a coupled finite volume and discrete element numerical method is used to numerically investigate the mechanisms that govern particle-laden gas flows and particulate fouling in idealized metal foam air-cooled heat exchangers. This paper provides a systematic analysis of the foulant distribution and the pressure drop due to the metal foam structure and the presence of fouling. The idealized Weaire-Phelan metal foam geometry serves as a good approximation to a real metal foam geometry. The pressure drop and deposition fraction follows a linear relation for sandstone cases, whereas for the sawdust cases, the pressure drop is sensibly invariant with time although a noticeable increase in deposition fraction with time is realized. The foulant residence time in addition to the correlations between pressure drop, deposition fraction, and inlet velocity can be used to optimize metal foam heat exchanger designs. Optimum heat exchanger performance is achieved by keeping the same fiber thickness of 0.17 mm at a high porosity at 97.87%. An increase in fluid carrier velocity promotes particle transport by means of particle interception thereby reducing the deposition fraction irrespective of foam geometry.

1. Introduction

The interphasial energy transfer between solid particles and a carrier fluid is universally prevalent in an array of industrial applications, ranging from condensers to belt guard aftercoolers, in the form of a classical air-cooled heat exchanger. The global heat exchanger market is expected to reach US $57.9 billion by 2016 and is projected to reach US $78.16 billion by 2020 [1]. Moreover, the global energy demand will increase by 37% over the next two decades [2]. The arduous challenge facing government bodies and heavy industries is to develop novel and innovative materials to maximize the efficient operation of a heat exchanger in an economically and environmentally sustainable manner. A recent report enunciates that innovative technologies could potentially save industries more than US $600 billion a year [3]. However, the overarching challenge lies in the inherent difficulty in selecting and implementing the many readily available materials or technologies.

Recent research has consistently shown that rib technology has the potential to enhance the overall heat transfer performance of a heat exchanger. The inclusion of ribbed channels in a high temperature heat exchanger (HTHE) was studied by Ma et al. [4] in the temperature ranged from 850 K to 1250 K and ratio of rib height to channel from 0.083 to 0.333. It was found that a 300% increase in the rib height amplifies heat transfer performance by 15–17% but the pressure drop increased by 12 times. Singh et al. [5] studied the heat transfer performance of a novel “V-down” ribbed channel

* Corresponding author.
E-mail address: emilie.sauret@qut.edu.au (E. Sauret).

http://dx.doi.org/10.1016/j.apenergy.2016.10.044
0306-2619/

in the Reynolds number ranged from 3000 to 15,000 for a rectangular duct solar air heater. A maximum Nusselt number is realized when the rib channel has an angle of attack of 60°. Liou et al. [6] examined the heat transfer and fluid flow behavior in a channel with periodic ribs for heat exchangers and electronic cooling devices. The flow acceleration and turbulence intensity played a pivotal role in influencing the heat transfer coefficient.

An innovative heat transfer procedure in the form of an immersed particle heat exchanger is proposed by Bellis and Catalano [7]. The particles act as an intermediate medium to exchange thermal energy between two-phase gas flows. The authors used 3D Reynolds Averaged Navier Stokes equations (RANS) and optimization techniques (SIMPLEX algorithm and Non-dominated Sorting Genetic Algorithm II) to maximize the heat exchanger efficiency of this novel heat exchanger. The major limitation of the mathematical model is that accurate particle-particle and particle-wall interactions have not been taken into account as the study assumes the dispersed phase occupies a low volume fraction. Secondly, only steady state particle dynamics have been considered. A variation to the geometric profile of standard heat exchangers have shown promising results in both heat transfer enhancement and fouling mitigation. For instance, Han et al. [8] numerically predicted flue-ash particle deposition rate on circular and oval tube-bundled heat exchangers and it was found that the oval tubes can reduce the fouling rate by 68.8%. A larger longitudinal tube pitch had a higher particulate deposit rate and heat transfer performance. Mavridou and Bouris [9] examined the fouling rate of a novel inline bundled heat exchanger with unequal tube diameters. It was found that the inline tube bundle with unequal sized tubes achieved about 30% reduction in particle deposition rate compared with the standard tube arrangement with identical tube diameters.

A promising material that has the potential to meet the high energy demand is the use of metal foams; a class of highly porous materials. The stochastic orientation of open-celled metal foam has an array of thermo-physical properties that make it beneficial in various applications such as Heating, Ventilation, Air-Conditioning, and Refrigeration systems (HVAC&R), electronics cooling, and waste heat recovery equipment [10]. Key properties include enhanced flow mixing capabilities due to high surface area to volume ratio and irregular tortuous ligament structure which has the potential to enhance heat transfer. Other properties include low weight, high strength and toughness [11]. The deployment of metal foams in heat exchangers have not come to fruition due to the lack of holistic information of metal foam heat exchanger technology in the current market.

Research has shown that the pressure drop from an elliptic pin fin heat sink with a metal foam insert decreases by increasing foam permeability [12]. A major observation is that an increase in Reynolds number yielded a 400% increase in Nusselt number. Wang et al. [13] numerically investigated heat transfer enhancement between a superheated steam and a receiver tube filled with metal foams in a solar thermal plant based on a parabolic trough collector (PTC). It was found that the Nusselt number increases about 10–12 times compared to a receiver tube without metal foam insert. Huisseune et al. [14] showed that a copper foam heat exchanger based on 45 pores per inch (PPI) is shown to exhibit a higher heat transfer rate than a bare tube bundle by a factor of six at the same fan power. Bai and Chung [11] found that a foam filled tube has a heat transfer rate two orders of magnitude higher than an open-tube macro channel. Bhattacharya and Mahajan [15] used experimental approach to study forced convection for electronics cooling applications. The heat transfer performance increases significantly when incorporating metal foams sandwiched between a fin based heat sink. However, they emphasized that the relative augmentation in heat transfer coefficient gradually declines with an increase in the number of fins.

The optimum operating conditions and performance characteristics of a counter flow heat pipe heat exchanger (HPHE) for the purposes of waste heat recovery were analyzed by Ma et al. [16]. It was found that a HPHE retrofitted with porous metal foams could potentially maximize the recovery of this waste heat thereby leading to rapid payback and lower greenhouse gas emissions. Bayomy et al. [17] numerically and experimentally examined the efficacy of an aluminium foam heat sink in the cooling of an Intel core i7 processor. The major conclusion is that an optimal design condition (that yields highest heat transfer with lowest pumping power) is achieved at a flow Reynolds number of 1353. This optimal design is evaluated based on the thermal efficiency index which takes into account the heat transfer and pressure drop across the aluminium foam. Wang et al. [18] studied the waste heat recovery performance of a metal foam filled thermoelectric generator (TEG) for cogeneration. The findings divulge that the maximum power generation was 29.75% higher than the value of an unfilled TEG.

A major limitation of the heat exchanger studies in all of the above cited publications is that all cases are based purely on single-phase flows, which is not the norm in many engineering systems. Most applications such as heat exchangers are based on multiphase flows such as particle-laden gas flows in air-cooled heat exchangers, HVAC&R, and electronics cooling [19]. The single-phase assumption provides an inaccurate description of the true pressure drop and effective thermal performance of metal foam heat exchangers. Secondly, like fin-based heat exchangers, metal foam heat exchangers are inevitably prone to particulate fouling over time consequently reducing the peak performance of a system. Particulate deposits on heat exchanger surfaces will not only reduce the heat transfer efficiency but also introduce a major uncertainty into the heat exchanger design [8]. Research has shown that the economic penalties incurred due to heat exchanger fouling amount to 0.25% of the gross domestic product (GDP) of industrialized countries [20]. Particulate fouling of ducts and heat exchanger networks (HENs) can hamper the proper functionality of many ventilating systems in buildings and can influence indoor air quality [21]. Crude Oil refinery operations have experienced increased Carbon Dioxide emissions caused by fouling in heat exchangers [22] while fouling on the evaporation tubes of a biomass-fired boiler significantly decreases boiler efficiency [23]. The reduction of energy consumption and greenhouse gases emanating from various applications such as industrial HEN is thus of paramount importance. Another weak point of the existing studies on particle-laden fluid flow is that the heat exchanger is based on low solids volume fraction (non-dense) flows (foulant is assumed to have no effect on the fluid flow characteristics). This assumption is not valid in many heat exchangers in the chemical, environmental protection, and energy generation industries [24–26].

The underlying mechanisms of dense particle-laden flows and particulate fouling (particulate deposition), and the actual thermo-hydraulic performance of metal foams due to fouling remain inconclusive. There is a scarcity of information based on multiphase flows and particulate fouling in metal foam heat exchangers. These limited studies are based on a number of assumptions and simplifications. An analytical approach implemented by Hooman et al. [27] was used to study the influence of particulate fouling on the thermo-hydraulic performance of aluminium metal foams. However, the study is based on a uniform fouling layer which is inconsistent with reality. Sauret and Hooman [28] used an Eulerian-Lagrangian numerical approach to assess the probability of particle deposition in an idealized metal foam heat exchanger for geothermal applications. However, the study assumes negligible momentum exchange between the disperse (solid particles) and continuous phase (carrier fluid), and negligible particle volume. Secondly, inter-particle hydrodynamic interactions and particle-wall micromechanics were not consid-