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Modeling and simulation of cross-flow transport membrane condenser heat exchangers

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ABSTRACT

Transport Membrane Condenser (TMC) is a promising technology that works based on the capillary condensation property of the nano-scale ceramic porous membrane materials and can recover both waste heat and water in various industrial applications. For applications with high volume flow rate such as in power plants, a large number of TMC heat exchangers are required, which highlights the importance of the optimum design for the TMC exchangers in order to obtain the maximum heat transfer and minimum cost of the TMC heat exchanger unit. In this paper, the effects of different tube spacing and the inlet water vapor mass fraction on the overall performance of a membrane-based heat exchanger have been studied numerically using a combined condensation model based on the capillary condensation and condensation on a solid wall. The results were obtained in terms of the Euler number, dimensionless volumetric heat transfer density, and contours of the water mass fraction and temperature distribution inside the TMC heat exchanger.

1. Introduction

Over 30% of the total energy loss in the US industry is in the form of thermal loss [1]. A considerable amount of this heat is of low grade, which has high water vapor content and low temperature. The low-grade heat recovery has been always a challenging issue since the low temperature of the flow stream and corrosive property of the condensed water makes the conventional heat exchangers inefficient. Transport Membrane Condenser (TMC) tubes, which work based on the capillary condensation in ceramic nano-porous material, can recover both water and latent heat in addition to sensible heat from low-grade flue gas stream [1,2].

A literature review shows that the performance of TMC heat exchangers is significantly higher than that of conventional heat exchangers with impermeable solid tubes. Bao et al. [3] studied the performance of a cross-flow TMC heat exchanger and compared their results with that of the impermeable stainless steel tubular heat exchanger. Their results showed that the total and convective Nusselt number in the TMC heat exchanger is 50% and between 50% to 80% higher than that of solid stainless steel heat exchangers respectively. Lin et al. [4] studied the heat transfer and condensation rate on a lab scale crossflow TMC heat exchanger numerically using a simplified single-phase multi-species model based a chemical reaction mechanism. Their results showed an acceptable agreement between the previous experimental and numerical results. The heat and water recovery capability of a single TMC tube was studied by Wang et al. [5] and Chen et al. [6] for various working conditions. In another study, Yu et al. [7] investigated the heat transfer capacity of a multichannel tubular ceramic heat exchanger. By comparing their result with the heat transfer capacity of a mono-channel tube, they concluded that the heat transfer rate in the multichannel membrane is higher. Hu et al. [8] studied the effects of membrane surface wettability on the heat and water recovery of a single TMC tube. The experimental results indicated that the membrane with the hydrophilic surface has higher condensation and heat transfer rates.

In this paper, the performance of a compact crossflow nanoporous membrane-based heat exchanger has been studied numerically to obtain the best configuration for the maximum volumetric heat transfer density under typical working conditions. A new semi-empirical condensation model based on the combination of the capillary condensation model and the wall based condensation model has been used. The model has been implemented in Ansys Fluent computational fluid dynamics code using User Defined Functions (UDFs) [9] and validated with the previous experiments. Contrary to the previous numerical simulations [4], the current model is also capable to simulate the heat and water transfer from the flue-gas domain into the porous zone and from there to the cooling water region in a TMC heat exchanger.

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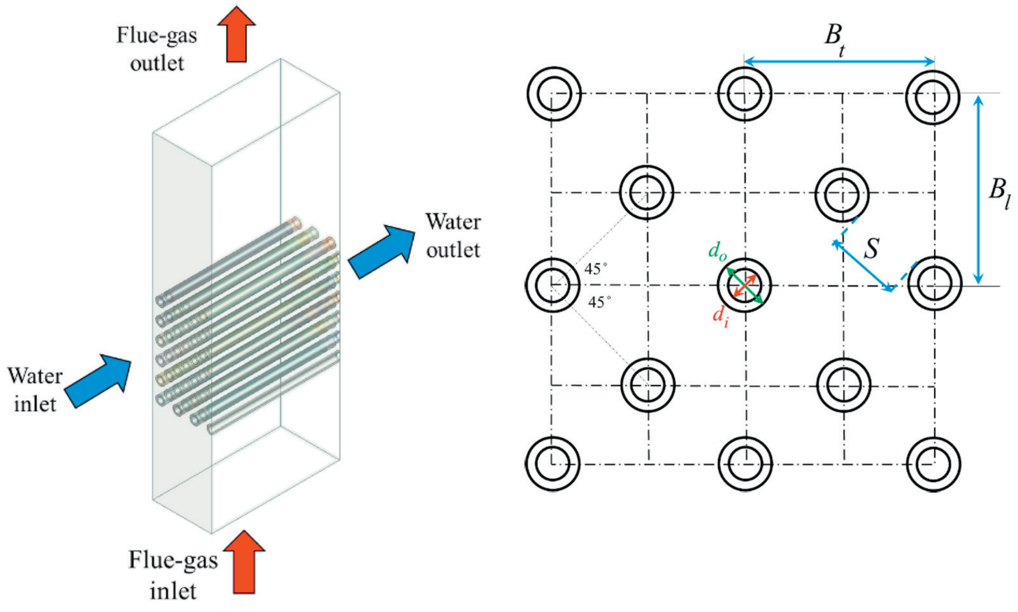

(a) (b)

Fig. 1. Schematic of a compact cross-flow TMC heat exchanger.

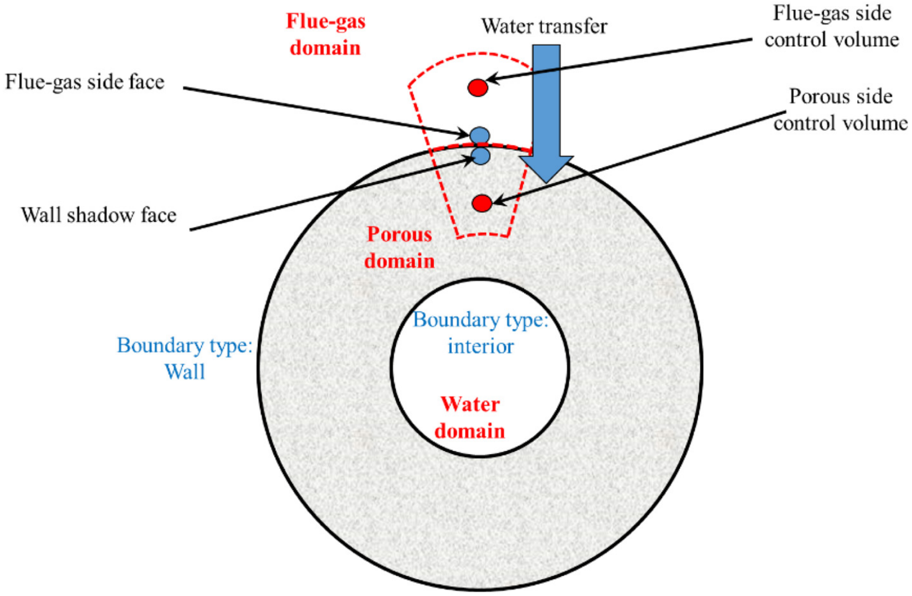

Fig. 2. Schematic of different zones and domains specified in the numerical setup.

Table 1
Inlet and outlet conditions for the experimental cases 1–11.

Test case		1	2	3	4	5	6	7	8	9	10	11
Flue inlet T	°F	179.2	179.6	180.3	179.0	179.8	180.9	179.1	180.3	178.5	161.2	161.0
Flue outlet T	°F	127.3	122.1	134.2	129.2	124.4	121.4	118.9	123.7	113.2	128.4	126.9
Water inlet FR	gpm	0.199	0.205	0.319	0.339	0.327	0.505	0.496	1.013	1.049	0.335	0.333
Water inlet T	°F	90.98	69.41	108.6	89.4	70.22	89.81	68.27	89.99	69.42	109.8	89.0
Water outlet T	°F	131.3	129.0	129.2	124.1	120.6	122.0	113.5	109.6	95.52	129.8	125.7
Flue-gas Flow	SCFH	2214	2214	2206	2216	2215	2210	2220	2217	2220	2213	2220