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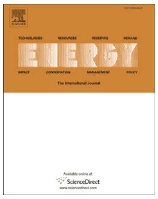

Application of field synergy principle for optimization fluid flow and convective heat transfer in a tube bundle of a pre-heater

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ABSTRACT

The big problems facing solar-assisted MED (multiple-effect distillation) desalination unit are the low efficiency and bulky heat exchangers, which worsen its systematic economic feasibility. In an attempt to develop heat transfer technologies with high energy efficiency, a mathematical study is established, and optimization analysis using FSP (field synergy principle) is proposed to support meaning of heat transfer enhancement of a pre-heater in a solar-assisted MED desalination unit. Numerical simulations are performed on fluid flow and heat transfer characteristics in a circular and elliptical tube bundle. The numerical results are analyzed using the concept of synergy angle and synergy number as an indication of synergy between velocity vector and temperature gradient fields. Heat transfer in elliptical tube bundle is enhanced significantly with increasing initial velocity of the feed seawater and field synergy number and decreasing of synergy angle. Under the same operating conditions of the two designs, the total average synergy angle is 78.97° and 66.31° in circular and elliptical tube bundle, respectively. Optimization of the pre-heater by FSP shows that in case of elliptical tube bundle design, the average synergy number and heat transfer rate are increased by 22.68% and 35.98% respectively.

1. Introduction

1.1. Solar-assisted MED (multiple-effect distillation) desalination unit

Seawater desalination is one of the most remarkable technologies to solve the increasing scarcity of fresh water. Solar-assisted MED desalination unit is considered as one of the most promising ways to effectively reduce water cost and minimize energy consumption due to the application of renewable energy and reusing low grade of waste heat [1,2]. Solar-assisted MED process consumes both thermal energy and mechanical energy to produce distilled water by using steam or waste heat from power plants and chemical processes.

In solar-assisted MED desalination systems heat exchangers are widely used, and circular tubes are the most commonly adopted heat transfer elements. The heat and mass transfer processes play important roles, which usually lead to bulky horizontal or vertical tube arrays heat exchangers. Recent analysis is mainly focused on the variations of the parameters that control the product cost (i.e. distilled water), which include specific power consumption [3], the specific heat transfer area, thermal performance ratio, conversion ratio and specific flow rate of the cooling water [4,5]. All these considerations are useful to increase the overall efficiency of solar-assisted MED desalination unit. However, due to high investment of solar collectors, an optimization operating parameters and enhancing heat transfer are a necessity to maximize the evaporator distillate production.

1.2. Brief literature review in optimization heat exchangers

In the literature review of heat exchangers for desalination field, Hisham et al. [6] studied the performance of parallel feed MEE (multiple-effect evaporation) system and the analysis was performed as a function of heating steam temperature, salinity of intake seawater and number of stages; the results indicated a better performance by across flow system. Li et al. [7] presented series of optimized heat transfer film coefficients of falling horizontal tube evaporators to increase the total heat transfer coefficients as well as reducing pipe diameter; these configurations found a basis for further developing of high efficiency heat transfer process and novel design of evaporators. Wei et al. [8] experimentally studied the laminar heat transfer characteristics of falling film evaporation on horizontal six tubes array made of enhanced and smooth tubes;

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Nomenclature

A	integral of advective term, kg K s^{-1}
C_p	heat capacity, J kg^{-1} K^{-1}
D_h	operating hydraulic diameter of tube = 4 × cross-sectional area of flow/wetted perimeter, m
a	semi-minor axis length of elliptic tube, m
b	semi-major axis length of elliptic tube, m
α	attack angle, °
Fc	average synergy number, dimensionless
h	heat transfer coefficient, W m^{-2} K^{-1}
K	thermal conductivity, W m^{-1} K^{-1}
k	turbulent kinetic energy, m^2 s^{-2}
L	length of computational domain, m
LP	longitudinal pitch, m
N	number of tubes
Nu	Nusselt number, dimensionless
ΔP	pressure drop, N m^{-2}
q	rate of heat transfer for the tube bundle, W
Re	Reynolds number, dimensionless
T	temperature, K
TP	transverse pitch, m
ΔT	actual temperature difference, K
$\vec{U}$	velocity vector, m/s
u, v, w	velocity components in x, y and z directions, m/s
TP	transverse pitch, m
x, y, z	cartesian coordinates, m

Greek symbols

ρ	density, kg m^{-3}
ε	turbulent energy dissipation rate, m^2 s^{-3}
S_{ij}	mean stress rate, s^{-1}
μ	viscosity, kg m^{-1} s^{-1}
Γ	diffusivity, kg m^{-1} s^{-1}
η	effectiveness
ψ	scalar
δ	thermal boundary layer thickness, m
β	local synergy angle, °
Ω	domain

Subscripts

as	adiabatic surface
f	fluid
i	inlet
l	longitudinal
o	outlet
s	surface
lm	log-mean
max	maximum
t	turbulent
e	certain point of the calculation region
j	number of times
avg	average

the tubes with both enhanced outer and inner surfaces could give high heat flux. K. Bourouni et al. [9] studied the heat and mass transfer in a horizontal tube falling film evaporation; the exchanger was made of polypropylene and designed to work at low temperatures (60 °C–90 °C); one-dimensional model was developed to predict the performance of the exchanger and the trends of evaporator. The application of LTLHP (low temperature lift heat pump) is intensified in seawater. Hoseong et al. [10] developed a novel heat exchanger, and the parameters were optimized by multi-scale approaches; results supported to decrease the cost of the heat exchanger and increase the performance of the LTLHP system. King et al. [11] suggested the LMTD (log-mean temperature difference) method to calculate the total heat transfer rate of such a heat exchanger; the results showed relatively low temperature differences in some practical situations.

In cross flow heat exchangers, flow conditions within circular tubes are operated at Reynolds numbers more than thousands in order to induce vortex motion or turbulence to enhance heat transfer. Heat transfer coefficient of the tube is associated with its position in the bundle. It was observed that the convection coefficient was increased gradually at the first row until approximately the fifth row of the tubes, after which there was little change in turbulence [12–14]. Also, László et al. [15] applied a genetic algorithm to the multi objective optimization of a two-dimensional cross flow tube heat exchanger with internal laminar flow.

During last few years, much works have been carried out on heat flow through elliptical tubes of heat exchangers. Elliptical tube aims at promoting the heat transfer coefficient and decreasing pressure drop with relative material mass reduction. However, results showed that the elliptical tubes arrangement had better overall performance and lower cost than the traditional circular tubes geometrically [16,17]. Hyun et al. [18] employed a hybrid evolutionary multi-objective algorithm that evaluated by RANS (Reynolds-averaged Navier–Stokes) in regard to enhance heat transfer and reduce pressure loss in a cooling channel with staggered elliptic dimples. From a design and fabrication stand-point, elliptical tubes provide a more practical solution than the complex circular tubes especially when attached with inner longitudinal coils or twisted fins. Table 1 reviews some previous experimental researches that showed the positive response of elliptical tube surface methodology to the interactions among design factors including number of rows, axis ratio, transversal tube pitch, longitudinal tube pitch, fluid velocity, volumetric flow rate towards the overall thermal hydraulic performance and compactness of the system.

1.3. FSP (field synergy principle)

Designing optimal shapes or configurations of various kinds of heat exchangers due to their relevance in various fields has attracted a lot of interest, since any attempt to improve their performance is desirable. Therefore, high effectiveness, small volume (hence low weight) and low cost are the common objectives in heat exchangers design.

Z.Y. Guo et al. [24] proposed a novel concept of optimizing and enhancing convective heat transfer of parabolic flows which is called field synergy principle (FSP), and was supported by numerical verifications; the results confirmed that the concept of enhancing parabolic convective heat transfer could be predicted by reducing the intersection angle between velocity vector and temperature gradient. Ji-An et al. [25] numerically studied the field synergy optimization and laminar convective heat transfer enhancement by multi-longitudinal vortex flow in enhanced DDIR (discrete double inclined ribs) tubes; the results showed that an optimum velocity field with high heat transfer performance and low flow resistance could be achieved by solving FSP equations.

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