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Study of a district heating system with the ring network technology and plate heat exchangers in a consumer substation

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ABSTRACT

Plate heat exchangers (PHE) have consolidated their position as key components of modern heating processes. They are widely accepted as the most suitable design for heat transfer applications in various processes, including the field of energy-efficient district heating (DH). This study refers to new DH coupling and control applied to a consumer substation. The concept introduces a new mass flow control model optimising the primary and secondary water streams to achieve remarkably higher temperature cooling in a new low temperature programme with diminished pressure losses. Here the operation of the ring network and the mass flow control in the substation are studied theoretically. A calculation procedure and transient models were constructed for the DH network, building structures, and heating heat exchangers. The PHE and its operation in the substation were studied by means of a corrugated plate model with five vertical parts and 10 elements. Variations in the flow rates, pressure losses, and overall heat transfer coefficients were received for the selected days. As a result almost equal heat capacity flows were found between the hot and cold sides of the PHE with maximum temperature cooling. The key performance factors of the heat exchanger, NTU and effectiveness, were monitored and the mean values obtained were 9.2 and 0.9, respectively.

1. Introduction

Plate heat exchangers (PHE) have consolidated their position as key components of modern heating processes. They are widely accepted as the most suitable design for heat transfer applications in various processes, including the field of energy-efficient district heating. Their frequent occurrence originates from their superb capability to produce remarkably high heat transfer coefficients with minimal fouling factors and physical size. According to Aminian et al. [1], plate heat exchangers weigh 95% less than typical shell-and-tube heat exchangers and provide 1000–1500 m^2 heat transfer surface per cubic metre of heat exchanger volume. However, the detailed design of a plate heat exchanger continues to be proprietary in nature although many new design approaches have been published in recent years. According to Gut and Pinto [2], there are no rigorous design methods for PHEs in the open literature, as there are for shell-and-tube exchangers. The design methods of PHEs are mostly owned by equipment manufacturers and are suited only for the exchangers that are marketed [3]. An exception is provided by Shah and Focke [4], who have presented a detailed step-by-step design procedure for rating and sizing a PHE, which is, however, restricted to parallel flow arrangements. In several works, the overall heat transfer coefficient U is considered invariable throughout the exchanger. Gut and Pinto [2] studied the modelling of plate heat exchangers with generalised configurations. They studied steady state heat transfer and thermal efficiency in different channels separately. They performed distributed U mathematical modelling of PHE and compared their results to those obtained with a simplified model in which a constant overall heat transfer coefficient was assumed. The results from the distributed U model showed that U varied from 866 to 1219 W/(m^2 °C), whereas the simplified model was solved with an average value of 1046 W/(m^2 °C). The main simulation results

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Nomenclature

A	heat exchanger surface area (m^2)
A_c	minimum cross-section area of single passage (m^2)
A_{ch}	cross-sectional area of channel (m^2)
A_{eff}	total effective surface area (m^2)
A_p	projected (single) plate area (m^2)
A_S	total surface area of plates, surface area of walls (m^2)
Bi	Biot number
b	mean channel spacing, m
C	constant
$\dot{C}_V$	heat capacity rate of ventilation, W/K
C_{min}	minimum heat capacity rate, W/K
c_p	specific heat capacity, J/(kg K)
C_S	heat capacity of walls, J/(kg K)
D	thickness of layer, m
D_e	equivalent diameter, m
D_p	port diameter, m
Fo	Fourier number
f	friction factor
G_{ch}	channel mass velocity, kg/(s m^2)
G_{WD}	conductance of windows and doors, W/K
G_p	mass velocity at port, kg/(s m^2)
h	heat transfer coefficient, W/(m^2 K)
K_p	constant
k	thermal conductivity, W/(m K)
k_w	conductivity of plate, W/(m K)
L	length, width, m
L_{eff}	effective length, m
L_p	projected length, m
L_w	plate width, m
M	constant
m	mass, kg
N_{ch}	number of channels
N_p	number of passes
Nu	Nusselt number
n	constant
p	pressure, Pa
Q	heat transfer rate, W
Q_{max}	maximum heat transfer rate, W
q_m	mass flow rate, kg/s
q_{mch}	mass flow rate per channel, kg/s
q_{Sk}	heat flow from interior air to surfaces of walls, kg/s
q_v	volume flow rate, m^3/s
Re	Reynolds number
R_{fc}	cold side fouling resistance (m^2 K/W)
R_{fh}	hot side fouling resistance (m^2 K/W)
s	plate thickness (m)
T	temperature (K)
T_{attic}	attic interior temperature
$T_{outdoor}$	outdoor temperature (K)
T_S	room temperature (K)
T_u	outdoor temperature (K)
ΔT_{ln}	logarithmic temperature difference (K)
t	time (s)
U	overall heat transfer coefficient (W/(m^2 K))

Greek symbols

α	thermal diffusivity (m^2/s)
β	chevron angle (°)
Δ	difference, step
ε	heat transfer effectiveness
ρ	density (kg/m^3)
Φ	heat flow, heat load (W)
Φ_{Air}	air conditioning heat losses (W)
Φ_c	heat losses by conduction (W)
Φ_F	heat conduction through floor (W)
Φ_L	heat losses by leakage air (W)
Φ_R	heat conduction through roof (W)
Φ_V	heat losses by ventilation (W)
Φ_W	heat conduction through walls (W)
Φ_{WD}	heat losses of windows and doors (W)
$\emptyset_k$	heat flow from radiators (W)
φ	rate of corrugation

Subscripts

c	cold fluid, channel
HP	heating plant
h	hot fluid
i, j	elements i and j
t	total
1, 2	inlet, outlet

Superscripts

n	time step

Abbreviations

CFD	computational fluid dynamics
DH	district heating
DHW	domestic hot water
GA	genetic algorithm
GDHS	geothermal district heating system
HP	heating plant
LMTD	log mean temperature difference
LTDH	low-temperature district heating
NTU	number of transfer units
PHE	plate heat exchanger

obtained with both models were very close, with a deviation of only 0.7% in the effectiveness of the exchanger. Gut and Pinto [2] presented a PHE modelling framework that is suitable for any configuration. The purpose of such a model was to study the influence of the configuration on the exchanger performance and further develop an optimisation method for rigorous configuration selection. Al-Dawery et al. [5] modelled PHEs using model linearisation and by applying PI, PID, and fuzzy logic controllers to the system. The model presents promising results as a preliminary basis for further studies, especially in implementing fuzzy logic control in a field which is otherwise dominated by PI and PID controllers. Dwivedi et al. [6] studied the dynamic responses to various step changes occurring in PHE models and their compatibility with measured results. Dovic et al. [7] constructed a model for predicting the correlations between the plate geometry and performance characteristics of a PHE. Their work is extremely useful in constructing case simulations when there is only limited knowledge of the geometrical attributes of the PHE. Zhang et al. [8] proposed a general three-dimensional distributed parameter model for evaluating and predicting the steady performance of a plate-fin heat exchanger. Peng and Ling [9] studied how a genetic algorithm combined with back-propagation neural networks can be used in finding the optimal design for plate-fin heat exchangers. The ability of genetic algorithms (GA) to predict and evaluate complex systems related to PHEs is also presented by Mishra et al. [10] and Xie et al. [11]. A similar GA approach was also taken by Najafi et al. [12] for optimisation of the system and achieving a set of optimal solutions that seek a balance between the highest total rate of heat transfer and the lowest total annual cost. These methods give an accurate