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Dynamic response and control analysis of cross flow heat exchangers under variable temperature and flow rate conditions

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A B S T R A C T

Crossflow heat exchangers are important facilities that are widely used in HAVC systems, such as data center cooling systems. The dynamic performance of the heat exchanger may have a significant effect on the performance of cooling systems. Characterizing and modeling the dynamic behaviors of cross flow heat exchangers in practical working conditions is important for both thermal management and control system design. Multiple variable input scenarios are common occurrences to the heat exchangers under practical operating conditions. In this paper, an established thermal dynamic model is solved numerically to predict the transient response of an unmixed–unmixed cross-flow heat exchanger, of the type that is widely used in data center cooling equipment. Detailed analyses of the transient response due to the time dependent fluid inlet temperature and flow rate are conducted. Cases for two fluid mass flow rate variation combinations, hot fluid inlet temperature and hot and cold fluid mass flow rate variation combinations are modeled and analyzed. Some of the most meaningful transient conditions such as step and linear ramp functions are used for the flow rate variation type for the hot and cold fluids, and step, ramp and exponential functions are applied to the fluid temperature at the entrance. Some of the modeling scenarios are based on control strategy design. The transient response results are also used to analyze some actual situations which are commonly seen for the cross flow heat exchangers used in data centers. The study and corresponding analysis provide fundamental insights into a cross flow heat exchanger which can be used to improve cooling unit performance and aid in the design of thermal control systems.

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1. Introduction

Heat exchangers are widely used in data center cooling systems. Rear door heat exchangers [1], in-row coolers, overhead heat exchangers and side car heat exchanger [2] are some examples that utilize crossflow heat exchangers in data centers. A CRAH (computer room air handler), which supplies centralized cooling air to the room, is in fact a water-to-air heat exchanger. A liquid to liquid heat exchanger is an important component of the coolant distribution unit (CDU), which supplies and distributes chilled water to the heat exchangers mentioned above. A cross flow configuration is one of the most widely used types of heat exchangers. Many of the current data center research studies are focusing on improving the cooling system performance, and designing self-regulating thermal control systems to improve energy efficiency and operational reliability of data centers. Understanding the dynamic behavior of the heat exchangers will be important for data center thermal management using different liquid cooling systems, hybrid air plus water cooling systems, and the corresponding control systems.

There is a considerable body of research on a cross flow heat exchanger's dynamic response. Based on the existing literature, previous studies characterize the problem using numerical methods, analytical methods, and experimental measurements. Gartner and Harrison [3] performed a study of the transient experimental characteristics of a fin-tube water-to-air cross flow heat exchanger under periodic fluid inlet temperature variations. Several analytical and numerical modeling methods have been developed for analyzing the dynamic behavior of cross flow heat exchangers due to a variation in fluid inlet temperature or fluid mass flow rate. Dusinberre [4] performed an early investigation of the transient behavior of a cross flow heat exchanger. A finite difference method was applied to solve the energy conservation equations, taking a specific case of a gas-to-gas cross flow heat exchanger. Later, Myers et al. [5] employed an integral technique to analyze a gas-to-gas cross flow heat exchanger. The model was simplified by assuming one mixed fluid. Transient characteristics of the average outlet temperature of two fluids under a step change to the inlet temperature were

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Nomenclature

A	area of heat transfer, m^2
A_c	area of cross section, m^2
c_p	fluid specific heat, J/kg K
C	heat exchanger wall specific heat, J/kg K
C^o	heat capacitance, J/K
E	capacity rate ratio
G	mass flux velocity, kg/m^2 s K
h	heat transfer coefficient, W/m^2 K
NTU	number of transfer units
NTU$'$	time dependent NTU due to mass flow rate variation
T	temperature, °C
TH	mean dimensionless outlet temperature of hot fluid
V	capacitance ratio
X, Y	dimensionless length
r	mass flow rate change ratio of mass flow rate
t^*	time taken for heat exchanger to reach steady state designed as the initial condition in this study
h'	changing heat transfer coefficient
k	thermal conductivity, W/m K
L	length of heat exchanger, m
t	dimensionless time
m	mass flow rate, kg/s
m'	changing mass flow rate
M	mass of the wall of heat exchanger, kg
N	dimensionless number
R	conductance ratio
T	dimensionless temperature
TC	mean dimensionless outlet temperature of cold fluid
x, y	heat exchanger physical length and direction
$p(t)$	fluid mass flow rate changing function
$f(t)$	transient boundary conditions to the inlet temperature of hot fluid

Greek letters

τ	time, s
α, β	parameters in inlet temperature
η	boundary condition functions constant number
ρ	density, kg/m^3
δ	parameter in variation function of fluid mass flow rate

Subscripts

h	hot fluid
w	wall of heat exchanger
out	outlet
c	cold fluid
in	inlet
Max	maximum

presented. Yamashita [6] numerically characterized the outlet temperature responses under the same step change as in Myers' study, without assuming a mixed fluid. One of the limitations of the method is it requires extensive simulation time. Some efforts have been made to develop analytical solution for the problem. Romie [7] performed the analysis of gas-to-gas cross flow heat exchangers using a double Laplace transform technique with neither gas mixed. A step variation to the inlet fluid temperature of either the hot side or the cold side was considered. Gvozdenac [8] and Spiga and Spiga [9] extended the work and investigated the transient behavior of gas-to-gas cross flow heat exchangers in the case of step change [8] and arbitrary inlet temperature variations, such as step, ramp, and exponential input functions [9]. In their work, two or three-fold Laplace transform techniques are used to solve the energy balance equations to achieve the temperature response. It is progressively more difficult to invert the transformed temperatures at the wall and the two fluids in the physical domain using the Laplace transform technique. Consequently, Chen and Chen [10] presented work on the transient analysis of gas-to-gas cross flow heat exchangers using the technique of a single Laplace transform, along with numerical inversion. The transient responses of a cross flow heat exchanger under step, ramp and-exponential variations are performed using a single Laplace transform in conjunction with a power series. Under some model assumptions, the analytic solutions for the simplified heat exchanger model equations are possible to obtain. More general model solutions must be obtained numerically. By utilizing a similar governing model, Mishra et al. [11] presented a numerical study on the unmixed–unmixed cross flow heat exchanger for step, ramp, as well as exponential variations in the hot fluid inlet temperature. The study considered the effect of the longitudinal conduction and axial dispersion on outlet temperature response, and model parameter effects are parametrically tested. For the mass flow rate variation study of a crossflow heat exchanger, there is no comprehensive literature on this topic due to the complexity of the transient analysis. Pearson [12] performed a study of the dynamic response of a fin-tube water-to-air heat exchanger under certain changes in the hot water flow rates. Both the numerical solution and the experimental data are presented and compared in the study. Roetzel and Xuan [13] briefly discussed the dynamic analysis for flow rate step variations with the assumption of a non-varying heat transfer coefficients. In the study conducted by Mishra et al. [14], the dynamic response of a cross flow heat exchanger due to perturbations in fluid temperatures and mass flow rates are investigated. Several different temperature and mass flow rate variation functions were also investigated. Hot fluid inlet temperature changes, combined with hot fluid mass flow rate changes, and hot fluid inlet temperature changes with two fluid mass flow rate changes are considered in their study.

Typically, data centers are operated under dynamic conditions due to server rack workload allocations that change both spatially and temporally. Additional dynamic situations may also arise, such as in the failure scenarios [15]. These lead to complex dynamic operating conditions for the cross flow heat exchanger. Due to this, it is common to see fluid inlet temperature changes combined with fluid mass flow rate changes, or cold fluid changes combined with hot fluid changes effecting to the heat exchangers. The control systems used by the data center cooling system may also generate multiple variations to the heat exchanger. For instance, the control system will respond to an increase in the cooling capacity, such as by increasing the cold fluid flow rate supplied to the heat exchanger, when the hot fluid inlet temperature is increased. Therefore, a complete understanding of the transient response of a cross flow heat exchanger under multiple variation inputs is important.

The present work investigates the dynamic performance of a single pass, unmixed–unmixed cross flow heat exchanger based on a two-dimensional transient model. In a manner similar to the study mentioned above, more variable input combination cases and an expanded set of scenarios are discussed (including the hot fluid inlet temperature, hot fluid mass flow rate, cold fluid mass flow rate variations). Instead of using the initial condition for which both of the two fluids and the heat exchanger wall temperature are set equal to the ambient temperature defined in [14], a specified equilibrium condition under specific inlet temperatures

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