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Development and verification of compact transient heat exchanger models using transient effectiveness methodologies

Tianyi Gao *, James Geer, Bahgat Sammakia

Department of Mechanical Engineering, Binghamton University-SUNY, Binghamton, NY 13902, United States

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ABSTRACT

Heat exchangers are important units in HVAC systems, such as the cooling systems used in data centers. The effectiveness of the heat exchangers significantly influences the thermal performance and energy efficiency of the cooling systems. Normally, the heat exchangers are designed for steady state operations. However, under practical working conditions, the events of changing operational conditions and working load may influence temperature and mass flow rate variations to the heat exchangers. For instance, typically data centers are dynamically operated due to the time and temperature dependent workload allocations. Therefore, the heat exchangers used in a data center operate under transient scenarios. Therefore, it is important to characterize the dynamic response of the heat exchanger. In this study, two compact transient modeling methods for heat exchangers are proposed. A transient effectiveness concept and model are used to develop transient modeling methodologies. Also, Computational Fluid Dynamic (CFD) heat exchanger models are developed using the compact transient methodologies. Verifications of the CFD compact models are carried out by comparing them with physics based thermal dynamic heat exchanger models and experimental measurements. The results show good agreement. Different heat exchanger configurations, including counter flow and cross flow heat exchangers are modeled and verified. The transient response of the heat exchanger under temperature variation, mass flow rate variation, and multiple variation combination scenarios are performed using the CFD compact models.

1. Introduction

Data center energy consumption and energy efficiency have become key issues and are expected to be constantly growing issues for the next few decades. About 1.5% of all electricity consumption in the United States has been related to data centers in the year 2006, while that number reached 2% in the year 2010. There was a 19% increase in the amount of electricity consumed globally by data centers between 2011 and 2012. Within data centers, the cooling systems constitute a large portion of the total data center energy consumption, and roughly 25–35% of the energy used is related to the cooling infrastructure [1,2]. Power use in data center IT equipment is also increasing rapidly every year [3]. Therefore, the required cooling capacity needs to be increased to keep mission critical facilities working within ASHRAE recommended operational conditions [4]. Improving the cooling efficiency of data center rooms is becoming a major challenge. There is a large body of research that has been conducted to innovative cooling technologies, such as liquid cooling, hybrid cooling and free air/water cooling solutions. All these cooling technologies are designed to improve the cooling efficiency by eliminating the need for CRAH units and chiller plants. Many of the new cooling solutions are currently being used by production data centers, such as rear door heat exchanger, in row cooler based hybrid cooling systems, airside or waterside economization, and warm water direct liquid cooling systems [5–8]. Heat exchangers are one of the key components in these cooling technologies.

Computational modeling and simulations are some of the most effective methods for designing new cooling technologies, and for efficiently operating and optimizing existing cooling systems. CFD code based computational simulations are a useful tool for analyzing and evaluating the cooling performance in data centers at prescribed performance levels. For instance, data centers are operated in dynamic conditions due to workload allocations that change both spatially and temporally. Additional dynamic situations may also arise due to failures or any other accident scenarios. Therefore, it becomes important for the dynamic cooling investigation to use CFD code to achieve a better understanding of these complex dynamic variations. Understanding the effect of these

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* Corresponding author at: Suite 1211, Center of Excellence (CoE) building, 85 Murray Hill Rd., Binghamton, NY 13902, United States. Tel.: +1 607 372 2798.

E-mail address: Tgao1@binghamton.edu (T. Gao).

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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_{wall}	specific heat of the wall of heat exchanger, J/kg K
C^o	fluid capacitance, J/K
h	heat transfer coefficient, W/m^2 K
h'	changing heat transfer coefficient
L	length of heat exchanger, m
m	initial/steady state mass flow rate, kg/s
m'	changing mass flow rate
M	mass of the wall of heat exchanger, kg
E	capacitance ratio, $(mc_p)_h/(mc_p)_c$
R	thermal resistance ratio, $(hA)_h/(hA)_c$
NTU	number of heat transfer unit
T	temperature, °C
$\bar{T}$	mean temperature
Q	heat transfer rate
x, y	heat exchanger physical length and direction
t	time, s
r	mass flow rate variation ratio, $r = m'/m$

Greek letters

ε	effectiveness
ε'	transient effectiveness
ε'_T	temperature dependent transient effectiveness/full transient effectiveness
ε'_m	mass flow rate dependent transient effectiveness/partial transient effectiveness
σ	standard deviation
η	constant value

Subscripts

h	hot fluid
c	cold fluid
$wall$	wall of heat exchanger
a	air
w	water
in	inlet
out	outlet
max	maximum
min	minimum

changes is of considerable importance for improving the energy efficiency and thermal reliability of cooling systems.

Heat exchangers are essential components of data center liquid and hybrid air plus water cooling systems. New cooling technologies and their effectiveness strongly influence the cooling performance. Rear door heat exchangers, in-row coolers, overhead heat exchangers, and sidecar heat exchangers are a few examples of liquid and hybrid cooling systems. An air to liquid heat exchanger is one of the main components of the dry cooler which is used as the waterside economizer. Computer Room Air Handler (CRAH) units which are used in legacy air cooling data centers consist of liquid to air cross flow heat exchangers. Generally, the heat exchangers are designed to perform under specific steady state conditions. However, transient variations occur due to changes of load demands or operational conditions especially in data center, such as server power increase and decrease, cooling unit failure, and other accident scenarios. Characterizing the dynamic response of the heat exchanger can significantly improve the performance of the cooling systems, such as in preventing thermal overshoot, which may have a detrimental impact on the electronic devices during transient events, and aid in the design of thermal control systems to be use for the development of high energy efficient self-sensing and self-regulating data centers [9].

A compact model should be as close to reality as possible in order to perform accurately and fast enough in a computational analysis. There is a great body of literature utilizing CFD modeling in characterizing the thermal management of data centers. Some studies have focused on detailed/compact component modeling in data centers, such as perforated tile patterns [10,11], server rack details [12,13], underfloor dynamics [14], compact server models [15–17], and many others [18,19]. Several studies have focused on developing steady state models of the heat exchangers in data center cooling systems, such as the rear door heat exchanger, the sidecar heat exchanger and the dry cooler [20–22]. The dynamic response and modeling of a heat exchanger are complex, due to many kinds of possible variation scenarios, including fluid temperature variations and mass flow rate variations. The situation becomes more complex when simulating a data center environment that operates in dynamic conditions. Multiple variation combinations may be applied to a heat exchanger when the heat exchangers are operated with a control system which dynamically adjusts the heat exchanger operating conditions. These adjustments are based on the applied heat load, or when the heat exchangers are operated in closed coupled heat transfer loops, which consist of multiple heat exchange components. The model should be able to represent the transient behavior of a heat exchanger under a variety of these scenarios. It is also important that the models be able to account for the effect of thermal capacitances for the fluids and the heat exchanger cores. In addition, the models should be simple enough to lower the computational time required to be used in a system level model. In order to develop an accurate and sufficiently simplified heat exchanger transient model, the compact modeling methodology is required.

In this work, heat exchanger compact transient modeling methodologies are proposed. The transient effectiveness concept and the corresponding models are used to develop these methodologies. The CFD compact model is developed using the proposed modeling methodologies. The usefulness and accuracy of the method are verified by comparing results with thermal dynamic heat exchanger models and experimental results. Several specific heat exchanger configurations, including counter flow and unmixed–unmixed cross flow, are investigated. Different transient scenarios including fluid inlet temperature variation, fluid mass flow rate variation, and multiple variation combination, are performed using the CFD compact models.

2. Compact modeling methodology I

2.1. Transient effectiveness concept and methodology

The concept of heat exchanger effectiveness (ε) is defined as the ratio of the actual heat transfer rate to the maximum possible heat transfer rate using in the compact ε-NTU steady state method, which has been proposed by Kay and London in [23]. The concept was extended to the time dependent effectiveness for each fluid by Cima and London in [24], as shown in Eqs. (1) and (2). If $C_{min} = C_h$, then Eq. (1) can be understood as “transient hot fluid temperature effectiveness” for cooling the hot fluid. If $C_{min} = C_c$, then Eq. (2) can be understood as “transient cold fluid temperature effectiveness” for heating the cold fluid.