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Experimental transient response of a minichannel heat exchanger with step flow variation

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ABSTRACT

Heat exchangers are essential components of many systems and their use is extended to include various industrial, chemical, and automotive applications. Heat exchanger behavior affects the total performance of a thermal system. Enhancing this critical component leads to improving the system overall performance and thus its energy efficiency. Since a heat exchanger operates in conjunction with other process equipment, its evaluation under a transient condition is crucial. A transient response of heat exchangers is necessary to evaluate the exchanger performance when subjected to a change in its conditions. The scarcity of experimental data on a transient response of heat exchangers in general and minichannel exchangers in particular is the main motivation for this research. This work is an investigation of an experimental characterization of the transient response of a cross flow liquid-air heat exchanger subjected to step changes in liquid mass flow rate. Hot fluid mass flow rate step changes of 0.5, 0.8, 1.5, and 2.0 are considered and the liquid outlet temperature response time is presented. The results are compared with the limited experimental work from the literature. While the outlet temperatures of both fluids do not respond instantaneously to the step change in the primary fluid mass flow rate, the cold fluid exhibits a faster response time than that of the hot fluid. The step variation increases the Reynolds number which results in a longer hot fluid response time to reach the steady state. The outcome of this work is valuable in the design, selection, and analysis of heat exchangers. The experimental data provided in this work can be used to establish a database for future advances in research. It also provides an overview of the characteristic behavior of certain parameters such as fluid temperatures, response time, and residence time when the heat exchanger is subjected to a change in the hot fluid mass flow rate.

1. Introduction

Industries worldwide are thriving to save space, energy and cost. Energy savings can be done either by using renewable energy sources instead of the conventional ones or by modifying the existing resources and system components to yield higher overall performance. One of these system components is the heat exchangers which are widely used to transfer heat in many applications such as: air conditioning, automotive, power generation, chemical, and oil & gas industries. The recent advances in technology made it necessary to use compact yet efficient heat exchangers.

High thermal performance can be affected by several factors such as heat exchanger types, tube/channel size, operating conditions, and working fluid. Studies on any of these parameters are important for the design of an efficient heat exchanger. Heat exchangers are usually part of a system and enhancing the efficiency of these exchangers contributes to the general system efficiency. Classification of heat exchangers can be found in Kandlikar and Grande [1] where they present the recent advances in channel diameter and define the range of 10 μm–200 μm as microchannels, between 200 μm and 3 mm as minichannels, and > 3 mm as conventional channels. The many research work on mini/microchannels heat exchangers has shown their outstanding thermal performance in addition to energy and space savings [2–6].

Steady state solutions of heat exchangers are widely accessible, well demonstrated, and strongly verified. The aforementioned statement cannot be said for the transient analysis. The performance of the heat exchanger varies with time and various interruptions in the operating conditions affect the exchanger behavior. A system performance varies when an improper control of a heat exchanger inlet conditions happens. Therefore, the change in the behavior of a heat exchanger affects the other components connected to it. When considering a transient analysis, a car radiator can be set as a good example. The main use of a radiator is to remove the undesired heat from the engine. Through the use of a thermostat, the amount of coolant that needs to be passed through to the radiator is controlled. This change in mass flow leads to the radiator working under transient conditions. For this regard,

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Nomenclature

A_c	channel cross section area, m^2
D	diameter, m
D_h	channel hydraulic diameter, m
L	channel length along the water fluid, m
$\dot{m}$	mass flow rate, kg/s
Re	Reynolds number
T	temperature, °C
t	time, s
t_{res}	resident time, s
V	fluid velocity, m/s
$\dot{\forall}$	volume flow rate m^3/s
X	mass flow step change

Greek symbols

β	area density, m^2/m^3
μ	dynamic viscosity
ρ	mass density, kg/m^3

Subscripts

a	air stream
c	cold fluid
f	final
i	initial
in	inlet
h	hot fluid
o	outlet
w	water stream

Superscripts

*	non-dimensional parameters

studying the transient response of a radiator is noteworthy for engine temperature optimization when mass flow perturbations occur.

Most of the analyses are based on the assumption that the heat exchanger works under steady state conditions, however, in practice, maintaining all the conditions fixed is a very challenging process. Several other issues may occur in practice such as at startup, shutdown, malfunction of the system and accidents. These variations affect the heat exchanger performance, therefore, it is essential to study the behavior of the heat exchanger when these issues occur for system improvement and to provide precautionary arrangements for its ultimate thermal performance.

The analyzation methods that tackle the transient response of heat exchangers are numerical, analytical, and experimental which can be used to assess the heat exchanger thermal behavior under transient conditions. Nevertheless, the lack of availability of experimental data leaves it open for present and future investigations. In order to validate the outcomes of analytical models or numerical simulations, some researchers verified their numerical work by analytical models or by experimental data conducted under steady state. Only very few work have been done experimentally and it involved a specific type of heat exchanger, flow arrangement or inlet condition change.

Studies also extended to include analytical investigation of the behavior of a single pass plate heat exchanger subjected to flow maldistribution by Srihari et al. [7]. Laplace transform method and numerical inversion of frequency were utilized to signify the effect of flow rate changes and back mixing on the transient response of the heat exchanger thermal performance. Time delay and time constant are extremely dependent on the flow rate change. Prashant Regulagadda [8] studied analytically the transient behavior of the heat exchanger in a Marnoch heat engine. He investigated this behavior using laminar and turbulent flows. A model created for a parallel flow heat exchanger with a step change in mass flow rate and its effect on the temperature of the working fluid was performed. His model was compared with previous research done by Yin and Jensen [9] and found good agreement.

Numerical analysis of a multi-pass cross flow heat exchanger to examine its transient performance was performed by Silaipillayarputhur and Idem [10]. The minimum capacity rate fluid was subjected to a step change in its inlet temperature and mass flow rate separately. Results of the multi-pass exchanger were compared with multi-pass parallel and counter cross flow heat exchangers. As a step change in mass flow rate is applied, it is noticed that the cross flow arrangement reduces the thermal performance of the heat exchanger when compared to parallel and counter flow arrangements. However, the main advantage of the cross flow arrangement is the enhanced thermal response time for three or more heat exchanger passes. Other advantage found was the decreased pressure loss in the tube side.

One of the early studies of the dynamic response of flow in heat exchangers was made by Stermole and Larson [11]. They used a double pipe counter current heat exchanger to conduct their experimental and theoretical analyses to investigate the dynamic response of such an exchanger. They found that as the flow rate varies, the system behaved linearly. Pearson et al. [12] used tube and plate-fin heat exchanger to study the dynamic response of air outlet temperature when a mass flow rate change is applied on the other fluid. They depended on the steady state experimental results to validate the numerical and mathematical models. Air outlet temperature and time constant results were compared to Gartner's model [13]. Their main findings are: the mathematical model satisfactory predicted the air outlet temperature of the heat exchanger for a step change in water mass flow rate and they extended Gartner's model to include a serpentine heat exchanger with fins. Idrissi et al. [14] investigated the transient response of temperature along a counter flow double pipe heat exchanger with a sudden change in the hot fluid mass flow rate. First order response to time constant was used to study the dynamic performance of the heat exchanger. Two responses were found from the cold fluid: the time response along the longitudinal axis to the counter flow and along the heat exchanger. Experimental data were used to verify the theoretical results. A linear decrease in time constant of the hot fluid was obtained as it undergoes a step change.

Transient behavior in a heat exchanger with two fluids, one is a single phase while the other has a constant temperature was performed by Yin and Jensen [9] for the case of step changes in temperature and mass flow rate. Explicit analytical solutions were acquired and verified by the numerical simulation at various operating conditions. They stated that since one of the fluid is subjected to constant temperature, it is independent of flow arrangement and their model can therefore be used for different flow arrangements.

Chopra and Prajapati [15] presented analytically the effect hot fluid mass flow rate changes and its composition percentages in a tube and fin heat exchanger on the outlet temperatures and the overall heat transfer coefficient. Two fluids were used, hot fluid, water-coolant was subjected to mass flow rate variations and the cold fluid air. A comparison of the obtained analytical solution was made with the steady state numerical results. It was found that as the hot fluid mass flow rate increased its outlet temperature decreased. When the hot fluid is more than 50% coolant to water mixture, the heat exchanger performance was found depreciating.

A cross flow heat exchanger used in data center was numerically modeled by del Valle et al. [16] using the finite difference method. Experiments were conducted to validate the model by subjecting the