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Transient response of a meso heat exchanger with temperature step variation

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ABSTRACT

Heat exchangers are common components of many industrial, residential, and automotive systems. In automotive, heat exchangers are employed in engine cooling and air conditioning to transfer the undesired heat from the engine or the passenger compartment as a condenser, evaporator, inter-cooler, heater core, radiator, and oil cooler. Since, the thermal performance of heat exchangers influences the under-hood automotive thermal management system, it is essential to characterize their dynamic response in general and specifically, when a sudden change to their operating parameters occur. Experimental measurements provide the scope for in depth understanding of the dynamic behavior of heat exchangers with respect to various parameters. This study investigates a liquid to gas cross flow meso heat exchanger subjected to transient conditions. Step variations in the hot fluid inlet temperature in the absence of mass flow rate disturbances was considered for 5 different levels ranging from 1.5 to 3.0, while other operating parameters are kept constant. The effect of step change on the thermal performance of a heat exchanger is demonstrated by both fluids outlet temperatures, heat transfer rate, effectiveness, and heat balance error. Results obtained show a faster response of the cold fluid outlet temperature compared to the hot fluid, however, an adverse effect is noticed for the heat transfer rate. Higher step changes in temperature lead to higher heat transfer rate, as expected; though, the hot side exhibited more heat transfer and higher effectiveness than the cold side. The hot fluid heat transfer rate and effectiveness display a non-linear increase reaching a peak, after which, it drops down at a slower rate compared to the cold fluid steady increase. A significant effect on normalized exit temperatures, heat transfer, and effectiveness at low step changes while it diminishes at higher step changes. The key element of this work is the use of meso heat exchanger to examine the transient conditions effect on its performance. This work covers a wide range of temperature step changes and aims to enrich the limited experimental database of dynamic response of heat exchangers. The outcome of this work is of interest to designers for thermal testing, characterization, and performance enhancement of compact heat exchangers.

1. Introductions

Heat exchangers are widely used equipment in many industries. Their significant existence in industrial systems is due to their need in transferring the heat from one medium to another. Many industrial systems are required to work with a certain temperature and in order to protect these systems from overheating and damaging the equipment; a heat exchanger is used to ensure the function of the system within safe operating conditions. Another gain from heat exchangers is to make use of the wasted heat released by a process and use it in another process that leads to energy and cost savings. A heat exchanger is a known equipment around the world and its uses are widely spread and not limited.

A heat exchanger classification by Shah and Seculik [1] arranged heat exchangers into categories according to many considerations such as: transfer process, surface compactness, number of fluids, flow arrangement, etc. One important category is the surface compactness due to the recent urgent needs in many applications to utilize compact and highly effective exchangers with reduced weight, space and cost. Their classification set a distinctive line distinguishing a compact from a conventional heat exchanger for gas to liquid as 700 m^2/m^3 above which any heat exchanger is considered compact. They considered the hydraulic diameter that can be used to separate compact from non compact exchangers to be $D_h \leq 6$ mm. within the compact heat exchangers category, other classification is considered, when the surface area to volume ratio is

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Nomenclature

A_c	channel cross section area, m^2
D	diameter, m
D_h	channel hydraulic diameter, m
HB	heat balance
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
∞	final
0	initial

Greek symbols

β	area density, m^2/m^3
ε	effectiveness
ε^*	generalized effectiveness
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
out	outlet
w	DI Water

Superscripts

*	non-dimensional parameter

more than 3000 m^2/m^3, the heat exchanger is called meso heat exchanger corresponding to a hydraulic diameter between 1 μm $\leq D_h \leq$ 1 mm.

The current investigation is concerned with the use of a heat exchanger that has a surface area density (β) of 4000 m^2/m^3 and according to [1], it is called a meso heat exchanger. Extensive studies regarding this type of a heat exchanger have been conducted to provide information regarding its thermal performance under steady state conditions [2–6]. These investigations proved that this type of heat exchangers delivers high heat transfer rate with enhanced thermal efficiency.

The requirements of any thermal system are higher heat transfer rate and efficiency, lower cost, and energy saving. A heat exchanger usually is a single component of a multi component system such as in residential HVAC or automotive industry. Consequently, enhancing the exchanger thermal performance results in improved overall system efficiency. Most heat exchangers analysis are performed assuming steady state operations. Any change that may occur on the steady state conditions of a process may lead to a substantial effect on its behavior and on the safety of operation. It is important to be acquainted with the knowledge on the dynamic performance of the heat exchanger for reasons of designing, controlling and safety handling. In most heat exchanger analyses, theoretical assumptions of steady state operations are made, however, it is very difficult to maintain these steady conditions and a transient behavior will occur. Adding to that, certain cases of starting, shutting down the system and breakdown may occur. This signifies the need for the transient response investigation of the heat exchanger.

Studies on heat exchangers working under steady state operation widely published and discussed whether numerical, analytical, or experimental analysis or a combination of any two of them. On the other hand, due to the difficulty in running a setup with transient state operating conditions, very limited investigations on the dynamic response of heat exchangers can be found and the available ones are using either numerical or analytical. Rare experimental work can be found with limited range of operating conditions. The following are some of the published work concerning investigating the transient response in heat exchangers.

An early numerical analysis was done by Romie [7] for a counter flow heat exchanger subjected to a step change in the inlet temperature of either of the working fluids. The exit temperature responses were studied using a finite difference method and shown in simple empirical equations. Gao et al. [8] performed another numerical study on transient response of step, ramp and exponential changes in the inlet temperature of an unmixed-unmixed cross flow heat exchanger. They used transient effectiveness method to build the analytical models that were used to analyze the transient behavior of cross flow heat exchangers. Their results were compared with the experimental transient response of an IBM rear door heat exchanger and was found to be in a good agreement.

Abdallah and Rooke [9] considered a finned-tube cross flow liquid to gas heat exchanger to study its thermal response. They applied a step change to the liquid inlet temperature and obtained the analytical solutions of the outlet temperatures as a function of time and location, using Laplace transform method. The effect of NTU on the thermal performance of the heat exchanger was presented. Other geometry consideration of the serpentine coil was also considered and they found that the tube bend possessed significant effect on some heat exchangers. Asgharpour et al. [10] studied analytically and experimentally the transient performance of coupled heat exchangers exposed to sudden change in inlet temperature. The effect of the reduction in the air inlet temperature of an air cooler on fluid exit temperatures was examined. An air-cooler heat exchanger was subjected to the temperature change by means of using an evaporative cooling. A Matlab model with sets of partial differential equations were employed in the analytical solution and results were verified using the experimental data. Their work also investigated other parameters effect on the transition time such as: connecting pipes length, mass flow rate, and the heat transfer coefficient.

Zhang et al. [11] experimentally and numerically studied the transient heat transfer of a C-shaped rod bundle heat exchanger that is used in reactors as a passive residual heat removal. To analyze the heat transfer, they used empirical equations along with the numerical turbulent model. Different turbulence models and eddy simulation were investigated then results were validated by experimental data. Higher heat transfer rate is found in the vertical section than in the horizontal section. Adding to that, flow velocity, turbulent mixing, and flow resistance showed an effect on the heat transfer of the heat exchanger. A minimum capacity rate fluid in a single pass cross flow heat exchanger was selected for step changes in temperature Syed and Idem [12]. Numerical analysis based on the finite difference method was used to present the prediction