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Transient behaviour of crossflow heat exchangers due to perturbations in temperature and flow

Manish Mishra [a,1], P.K. Das [b,*], Sunil Sarangi [c,2]

[a] *Mechanical Engineering Department, Government Engineering College, Raipur 492 010, India*
[b] *Department of Mechanical Engineering, Indian Institute of Technology, Kharagpur 721 302, India*
[c] *Cryogenic Engineering Centre, Indian Institute of Technology, Kharagpur 721 302, India*

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Abstract

Transient temperature response of crossflow heat exchangers having finite wall capacitance with both fluids unmixed is investigated numerically for perturbations provided in both temperature and flow. Results are presented for step and ramp change in flow rate of hot and cold fluids, and step, ramp, exponential and sinusoidal variation in hot fluid inlet temperature.
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Keywords: Crossflow; Flow transients; Heat exchanger; Transient behaviour

1. Introduction

Heat exchangers are generally designed to meet certain performance requirements under steady operating conditions. However, transient response of heat exchangers needs to be known for designing the control strategy of different HVAC systems, cryogenic and chemical process plants. Problems such as start-up, shutdown, failure and accidents have motivated investigations of transient thermal response in crossflow heat exchangers. It also helps the designer to find a solution of the time dependent temperature problems, essential for thermal stress analyses.

Dynamic behaviour of crossflow heat exchanger with excitation in inlet temperature of one or both the fluids is a topic of active research interest [1–4]. In practice the mass flow rate of the fluid also receives disturbances with time in addition to perturbation in temperature. In an industrial installation the heat exchanger may also be subjected to variable flow rates either at one or both the inlets during its operation. The transient response due to this effect is also required to be studied in order to have a complete appraisal of the dynamic performance of heat exchangers under diverse situations of operation and control.

A theoretical and experimental study by Stermole and Larson [5] of the transient and frequency response has been done for a double pipe steam-to-water heat exchanger. The partial differential equation model used for predicting response was in good agreement with experimental data. Dynamic response of the discharge air temperature to changes in the hot water flow rates has been studied by Pearson et al. [6] for a commercial finned serpentine tube water-to-air heat exchanger. A first order dynamic model was solved and compared with numerical and experimental results. The transient behaviour of double pipe and shell and tube heat exchangers has been analysed by Lachi et al. [7] for a sudden change of flow rate in one of the two fluids. A two-parameter model with a time lag and time constant, giving the analytical expressions of the time constant has been proposed. The experimental results have also been presented showing good agreement with the theoretical predictions. The spatial variation of transient response of temperatures along a countercurrent heat

* Corresponding author. Tel.: +91 3222 282916; fax: +91 3222 2755303.
E-mail addresses: mishra_md@yahoo.com (M. Mishra), pkd@mech.iitkgp.ernet.in (P.K. Das), ssarangi@hijli.iitkgp.ernet.in (S. Sarangi).
[1] Tel.: +91 771 2253155; fax: +91 771 2254600.
[2] Tel.: +91 3222 283592; fax: +91 3222 2755303.

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Nomenclature

A	area of heat transfer, m^2
A_c	area of cross-section, m^2
c	specific heat of fluid, J/kg K
C	specific heat of the wall material, J/kg K
E	capacity rate ratio $= \frac{(mc)_b}{(mc)_a}$
G	mass flux velocity, kg/m^2 s
h	heat transfer coefficient, W/m^2 K
h'	$\gamma^{\beta} \cdot$ h, W/m^2 K
L	heat exchanger length, m
m	initial mass flow rate of fluid, kg/s
m'	mass flow rate after time θ, kg/s
M	mass of the separating sheet, kg
N	$\frac{hA}{mc}$, dimensionless
NTU	initial number of transfer units
NTU′	number of transfer units, Eq. (7)
R	conductance ratio $= \frac{(hA)_b}{(hA)_a}$
t	temperature, °C
$T = \frac{t - t_{b,in}}{t_{REF} - t_{b,in}}$	dimensionless temperature
$\overline{T}$	mean dimensionless temperature
u, v	velocity in x- and y-direction, m/s
V	capacitance ratio $= \frac{LA_c\rho c}{MC}$
x, y	space direction, m
$X = \left(\frac{hA}{mc}\right)_a \frac{x}{L_a}$	dimensionless length
$Y = \left(\frac{hA}{mc}\right)_b \frac{y}{L_b}$	dimensionless length

Greek symbols

γ	m'/m
$\theta = \frac{(hA)_a \tau}{MC}$	dimensionless time
τ	time, s
$\phi(\cdot)$	perturbation in hot fluid inlet temperature
$\phi_1(\cdot)$	perturbation in mass flow rate

Subscripts

a	hot fluid
b	cold fluid
ex	exit
in	inlet
max	maximum
min	minimum
REF	a reference value
w	wall

exchanger for a flow rate step in internal hot fluid has also been presented by Abdelghani-Idrissi et al. [8]. The dynamic behaviour has been approximated by a first order response with a time constant. The theoretical result was reported to be in close match with the experimental data.

On the other hand Xuan and Roetzel [9] suggested a method based on the numerical inversion of Laplace transform to find out the combined response of flow rate and temperature variation for a shell and tube heat exchanger. Later, the response of a counterflow heat exchanger to step change of flow rates has been obtained by Romie [10] using double Laplace transform.

In their pioneering book, Roetzel and Xuan [3] analysed the dynamic behaviour of crossflow heat exchangers of different arrangements. The analysis to calculate the outlet temperature response to special and arbitrary inlet temperature and flow rate disturbances has been presented. Solution methodologies by Laplace transform as well as finite difference scheme have been discussed. Effects of flow maldistribution and wall heat conduction resistance have also been discussed and considered. A large number of examples with various combinations of temperature and flow transients have been considered.

The present work investigates the transient performance of a direct transfer, single pass crossflow heat exchanger with finite core capacity. The temperature response of the fluid streams as well as the separator plate has been obtained solving the conservation equations by finite difference formulation for step, ramp as well as exponential variation of the hot fluid inlet temperature and step and ramp variation in flow rates. The analysis has been done for the generalised case of unmixed fluid streams and finite capacitance of fluids and metal wall.

2. Mathematical modelling

A direct-transfer, two-fluid, crossflow, multilayer plate-fin heat exchanger is shown schematically in Fig. 1(a).

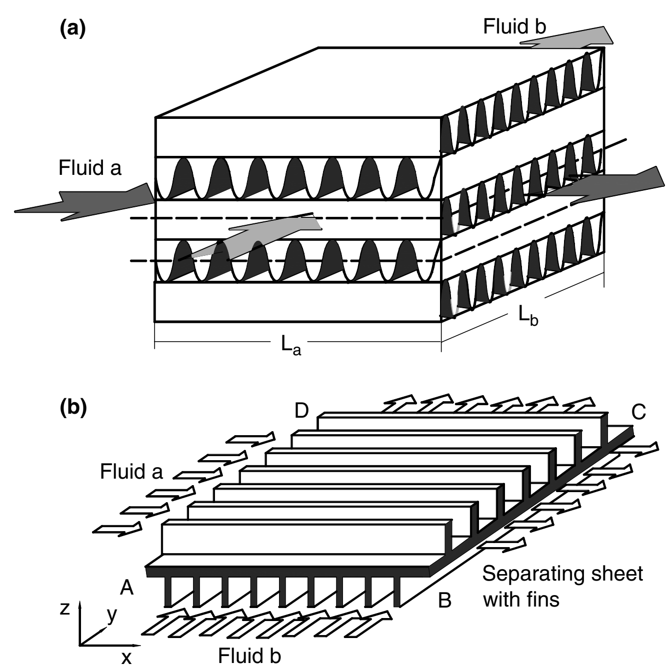

Fig. 1. Crossflow heat exchanger (a) schematic representation, and (b) symmetric module considered for analysis.

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