Transient Behaviour of Crossflow Heat Exchangers Due to Perturbations in Temperature and Flow

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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.

Key words: crossflow, flow-transients, heat exchanger, transient behaviour.

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' - γ^β. 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

$X = (\frac{hA}{mc})_a \frac{x}{L_a}$, dimensionless length

$Y = (\frac{hA}{mc})_b \frac{y}{L_b}$, dimensionless length

Greek Symbols

γ - m'/m

$\theta = \frac{(hA)_a \tau}{MC}$, dimensionless time

τ - time, s

ϕ(.) – perturbation in hot fluid inlet temperature

ϕ1(.) - 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

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 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 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). Fluid ‘a’ and fluid ‘b’ exchanges thermal energy through a separating solid plate while flowing through this heat exchanger in a direction normal to each other. Without any loss of generality, it is assumed that ‘a’ is the hot stream, which is subjected to a specified temperature variation at the inlet, while ‘b’ is the cold stream, which enters the heat exchanger with a known constant temperature. Following assumptions are made for the mathematical analysis.

1. Both fluids are single phase, unmixed and do not contain any volumetric source of heat generation.
2. The exchanger shell or shroud is adiabatic and the effects of the asymmetry in the top and bottom layers are neglected. Therefore the heat exchanger may be assumed to comprise of a number of symmetric sections as shown by dotted lines in Fig. 1(a) and in details in Fig. 1(b).
3. The thermo-physical properties of both the fluids and walls are constant and uniform.
4. The primary and secondary areas of the separating plate have been lumped together, so that the variation of wall temperature is also two-dimensional.
5. The thermal resistance on both sides comprising of film heat transfer coefficient of primary and secondary surface and fouling resistance are uniform. However, film heat transfer co-efficient is a sole function of fluid velocity and changes with time as the flow rate also changes. For the sake of simplicity heat transfer co-efficient has been considered in a functional form as given in eq. (3). The effect of fouling resistance (which is independent of velocity) has not been considered in the examples presented but can be taken care of by the reported algorithm.
6. Heat transfer area per unit base area and surface configurations are constant.
7. Variation of temperature in the fluid streams in a direction normal to the separating plate (z-direction) is neglected.

In the present case, disturbance or variation is assumed in mass flow rate of either one or both the streams. Both step and ramp variations have been considered. Assuming the ratio of the mass flow rate at time θ, to that at initial time level, as γ, one gets

$$m_a' = \gamma_a \, m_a \text{ and } m_b' = \gamma_b \, m_b \tag{1}$$

At time $\theta = 0$, $\gamma_a = \gamma_b = 1$, and

$$\theta = \theta,\ \gamma_a = \gamma_b = \phi 1(\theta). \tag{2}$$

The flow is assumed to be fully developed turbulent only, making the heat transfer coefficient h proportional to G^β and hence to m^β with β=0.8 (as suggested by the classical Dittus-Boelter correlation). Thus

$$h_a' = \gamma_a^{\beta}.\, h_a, \text{ and } h_b' = \gamma_b^{\beta}.\, h_b \tag{3}$$

Applying the assumptions stated, conservation of energy for the wall and the two fluids can be expressed in non-dimensional form as given below,

$$\frac{\partial T_w}{\partial \theta} = \gamma_a^\beta . T_a + R.\gamma_b^\beta . T_b - (\gamma_a^\beta + R.\gamma_b^\beta).T_w \tag{4}$$

$$V_a . \frac{\partial T_a}{\partial \theta} = \gamma_a^\beta .(T_w - T_a) - \gamma_a . \frac{\partial T_a}{\partial X} \tag{5}$$

$$\frac{V_b}{R} \frac{\partial T_b}{\partial \theta} = \gamma_b^\beta .(T_w - T_b) - \gamma_b . \frac{\partial T_b}{\partial Y} \tag{6}$$

The value of t_{REF} in the dimensionless temperature is arbitrary (provided that $t_{REF} \neq t_{b,\,in}$)

Now NTU' is given by the relation:

$$\frac{1}{NTU'} = (m'c)_{min}\left[\frac{1}{(h'A)_a} + \frac{1}{(h'A)_b}\right] = (m'c)_{min}\left[\frac{1}{\gamma_a^\beta (hA)_a} + \frac{1}{\gamma_b^\beta (hA)_b}\right] \tag{7}$$

If $(m'c)_a=(m'c)_{min}$, i.e. $\frac{\gamma_b}{\gamma_a}E > 1$

$$N_a = NTU'.\gamma_a \left(\frac{1}{\gamma_a^\beta} + \frac{1}{R.\gamma_b^\beta}\right) \quad (8)$$

$$N_b = \frac{NTU'.\gamma_a}{E} \left(\frac{R}{\gamma_a^\beta} + \frac{1}{\gamma_b^\beta}\right) \quad (9)$$

If $(m'c)_b=(m'c)_{min}$, i.e. $\frac{\gamma_b}{\gamma_a}E < 1$

$$N_a = NTU'.\gamma_b.E\left(\frac{1}{\gamma_a^\beta} + \frac{1}{R.\gamma_b^\beta}\right) \quad (10)$$

$$N_b = NTU'.\gamma_b \left(\frac{R}{\gamma_a^\beta} + \frac{1}{\gamma_b^\beta}\right) \quad (11)$$

The initial and boundary conditions are,

$$T_a(X,Y,0) = T_b(X,Y,0) = T_w(X,Y,0) = 0, \quad (12)$$

$$\text{At } \theta=0,\ \gamma_a = \gamma_b = 1 \quad (13)$$

$$\theta = \theta,\ \gamma_a = \phi 1(\theta) \text{ and/or } \gamma_b = \phi 1(\theta). \quad (14)$$

$$T_b(X,0,\theta) = 0 \quad (15)$$

With temperature transients,

$$T_a(0,Y,\theta) = \phi(\theta)\ . \quad (16)$$

If there is no temperature transient, then

$$T_a(0,Y,\theta) = T_a(0,Y,0)=1 \quad (17)$$

$\phi1(\theta)$ used in eq. (14) is the perturbation in mass flow rate of the two fluids. It may or may not be equal for the two fluids. Assuming it to be the same for both the sides.

$$\phi1(\theta) = \begin{cases} \gamma, \text{for step change in flow rates} \\ (\theta+1), \text{for ramp chang in flow rates} \end{cases} \tag{18}$$

Similarly $\phi(\theta)$ [eq. (16)] is the perturbation in inlet temperature of the hot fluid.

$$\phi(\theta) = \begin{cases} 1; \quad \text{for step input} \\ \begin{bmatrix} \alpha\theta, \ \theta \le 1 \\ 1, \ \theta \ge 1 \end{bmatrix}; \text{for ramp input} \\ 1 - e^{-\alpha\theta}; \ \text{for exponential input} \\ \sin(\alpha\theta); \text{for sinusoidal input} \end{cases} \tag{19}$$

3. Method of Solution

The conservation equations are discretised using the implicit finite difference technique [11]. Forward difference scheme is used for time derivatives, while upwind scheme is used for the first order space derivative respectively. The difference equations along with the boundary conditions are solved using Gauss-Seidel iterative technique. The convergence of the solution has been checked by varying the number of space grids and size of the time steps. The solution gives the two-dimensional temperature distribution for both the fluids as well as separator plate. Additionally one may calculate the mean exit temperatures as follows.

$$\overline{T}_{a,ex} = \frac{\int_0^{Na} T_{a,ex}.u\,dy}{\int_0^{Na} u\,dy} \quad \text{and} \quad \overline{T}_{b,ex} = \frac{\int_0^{Nb} T_{b,ex}.v\,dx}{\int_0^{Nb} v\,dx} \tag{19}$$

To check the validity of the numerical scheme, the results of the present investigation have been compared with available analytical results using Laplace transform [11] for a balanced gas-to-gas crossflow heat exchangers in the absence of flow variation with conductance ratio of 1. Fig. 2 depicts excellent agreements between the results of present investigation and those obtained analytically [12] for step input.

4. Results and Discussion

The dynamic performance of the heat exchanger was studied over a wide range of parameters as well as for a sufficient time duration so that steady state conditions are obtained for each individual excitation. Some of the salient results are discussed below.

4.1 Transient behaviour due to variation in flow only

Fig. 3 depicts the exit temperature response of the hot and the cold fluids due to change in flow rate in the absence of any temperature perturbation. Comparing with the case of no flow transients, when γ_a=γ_b=1.25, there is large increase in flow rates on both the sides. This increases the rate of heat transfer, and as a result the mean exit temperature of the hot fluid decreases and that of the cold fluid increases. When only hot fluid is stepped (γ_a = 1.25), significant increase in hot fluid mean exit temperature occurs while the increase in the cold fluid exit temperature is comparatively smaller. Similarly when only cold fluid is stepped, an increase in the mass flow rate of cold fluid for an unchanged value of the heat capacity rate of the other stream causes a reduction in cold fluid mean exit temperature with a marginal reduction in hot fluid exit temperature [Fig. 3(a)].

For the combination of step and ramp increase in flow, the behaviour obtained is qualitatively same as that observed in the earlier case. However, the relative amount of increase or decrease in exit temperatures are more relevant, as the increase in flow is higher than that in case of step increase. Also in case of ramp increase, there is continuous increase in flow with time, which makes the exit temperature diverging for that particular fluid. For the other fluid (stepped) the tendency to reach to steady state is very fast [Fig. 3(b)].

4.2 Transient behaviour due to variation in flow as well as temperature

The effect of step and ramp inputs in hot fluid flow rate only (keeping γ_b=1) with step change in inlet temperature of hot fluid has been studied and shown in Fig. 4. Time taken to reach to steady state is more for both hot and the cold fluids with the increase in NTU. The magnitude of the mean exit temperature decreases for the hot fluid and increases for the cold fluid with increase in NTU showing higher value of heat transfer due to availability of larger heat transfer area. Similar effects are also observed for a ramp increase in flow rate of the hot fluid. In the same figure the results have also been compared for the exit temperature behaviour with variation in temperature only (no flow variation). It shows that due to flow variation the exit temperatures come comparatively closer to each other at different NTUs. Further, time taken to reach steady state reduces due to the increase in flow rate of the hot fluid. The effect of step ratio γ_a on the mean exit temperatures of hot and cold fluids has also been seen in Fig. 5. When there is sudden increase in hot fluid flow rate, the time taken to reach the steady state is less, and for the smaller step ratio time taken is longer. This shows that the increase in hot fluid flow rate not only increases the exit temperatures, but at the same time the effect of transients also reduces.

The combined effect of temperature and flow transients with flow disturbance in both the fluids has been shown in Fig. 6 for step change in hot fluid inlet temperature and step variation in fluid flow rates. Different combinations of γ_a and γ_b show that the mean exit temperature of both the fluids increases or decreases with the simultaneous increase or decrease in flow rates on both the sides. When flow rate of hot fluid is given step increase while cold fluid is given stepped reduction, the mean exit temperature of both the fluids increases. A reverse effect is seen when flow rate of hot fluid is decreased and that of cold fluid is increased. The effect is similar for ramp and exponential inputs to the hot fluid inlet temperature. The behaviour is similar to that obtained when the perturbation in inlet temperature is absent as shown in Fig. 3(a).

Fig. 7 further depicts the combination of step and ramp change in flow rates for step, ramp, exponential and sinusoidal change in hot fluid inlet temperature. When flow is provided with ramp increase in both the fluids, the tendency to reach to the steady state value is faster with respect to the case when there is no disturbance. When flow rate of the hot fluid is given the ramp increase keeping flow rate of cold fluid stepped, the mean exit temperature of both the fluids increases. A reverse effect is obtained when cold fluid is given ramp increase while hot fluid is stepped. This variation is similar for step, ramp and exponential excitation in inlet temperature of hot fluid. In case of sinusoidal excitation in hot fluid inlet temperature, the amplitude of mean exit temperature continuously increases if a ramp change is provided to hot fluid flow rate, while the cold fluid is stepped. The reverse effect is observed when ramp change is given to the cold fluid flow rate, hot fluid being stepped. However, the increase or decrease of exit temperatures depends upon the relative magnitude of the stepping or ramp change given to the two fluids.

5. Conclusion

A numerical scheme has been developed for determining the transient behaviour of crossflow heat exchangers using finite difference method. Dynamic performance of the heat exchanger has been studied in response to perturbations in temperature as well in flow rates for finite core capacity. Contrary to the conventional practice, ramp and exponential input functions of temperature transients have been taken in a modified form, which represent the transients generally observed in practice. Results have been presented for different combinations of step or ramp change in flow rate of the two fluids and step, ramp, exponential or sinusoidal excitation in hot fluid inlet temperature. Mean exit temperature of both the fluids increases or decreases with the simultaneous increase or decrease in flow rate of the two fluids. Also, the increase or decrease in exit temperatures depends upon the relative magnitude of the disturbance provided to the two fluids. An increase in mean exit temperatures is observed when the disturbance is more in hot fluid, while a decrease is observed with the larger disturbance being in cold fluid.

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Figure captions

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

Figure 2 Comparison of the numerical solutions with the analytical results of Spiga and Spiga [12] for step input with E=R=1, V=0, and $\gamma_a=\gamma_b=1$.

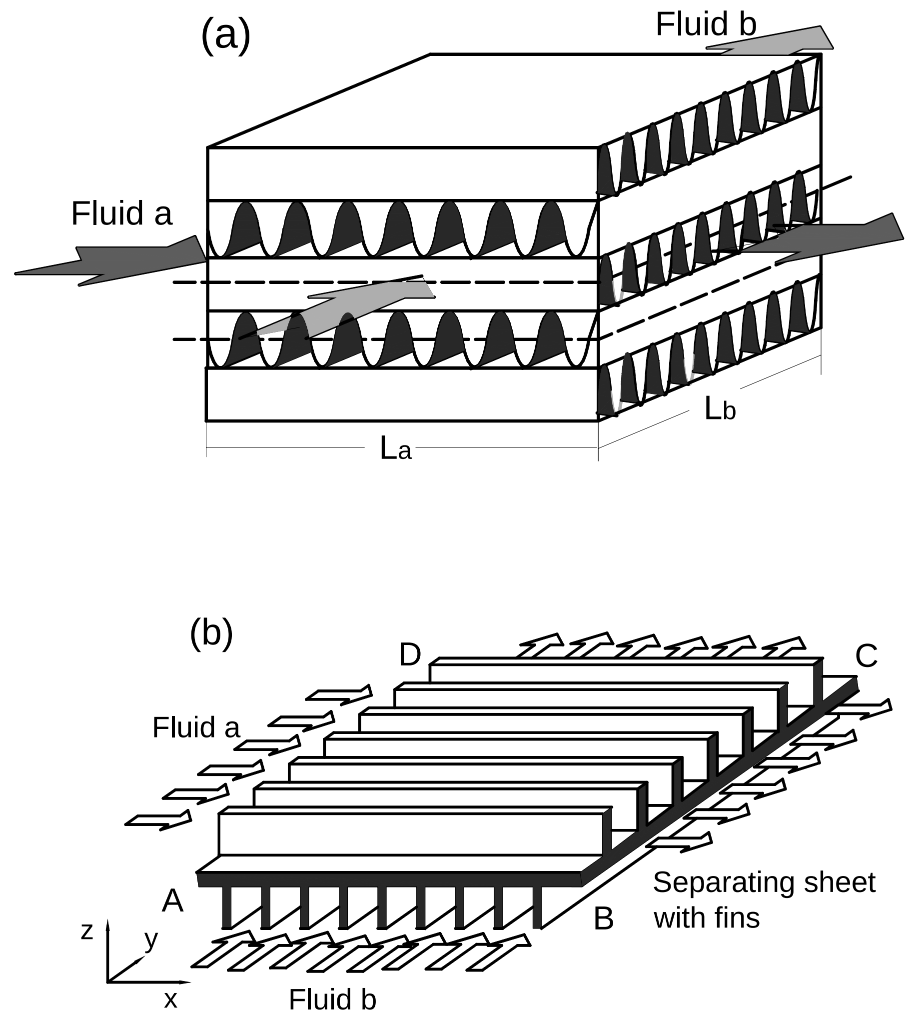
Figure 3 Exit temperature response of the hot and cold fluids for (a) step excitation in flow rates, (b) combination of step and ramp change in the two fluid streams.

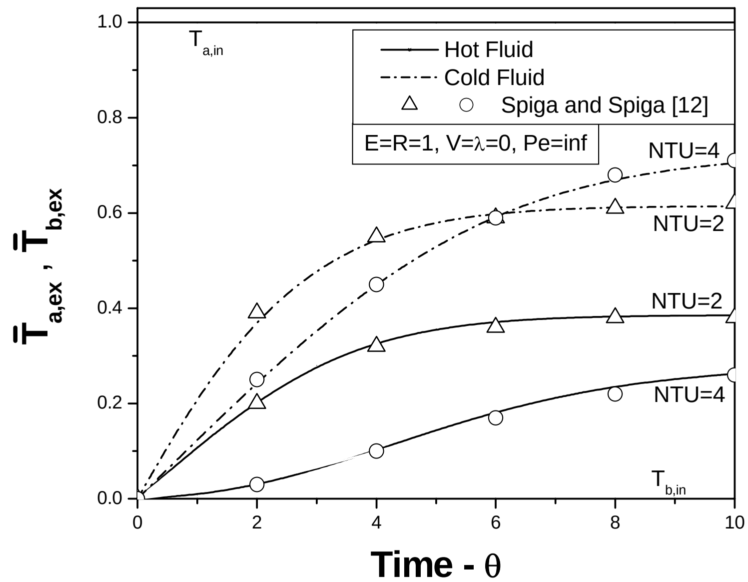
Figure 4 Effect of flow transients due to step (a - hot, b - cold) and ramp (c - hot, d – cold) inputs in flow rates with step excitation in hot fluid inlet temperature.

Figure 5 The combined effect of temperature (step) and flow transients with step size on fluid flow rates of both fluids on mean exit temperatures of (a) hot and (b) cold fluids.

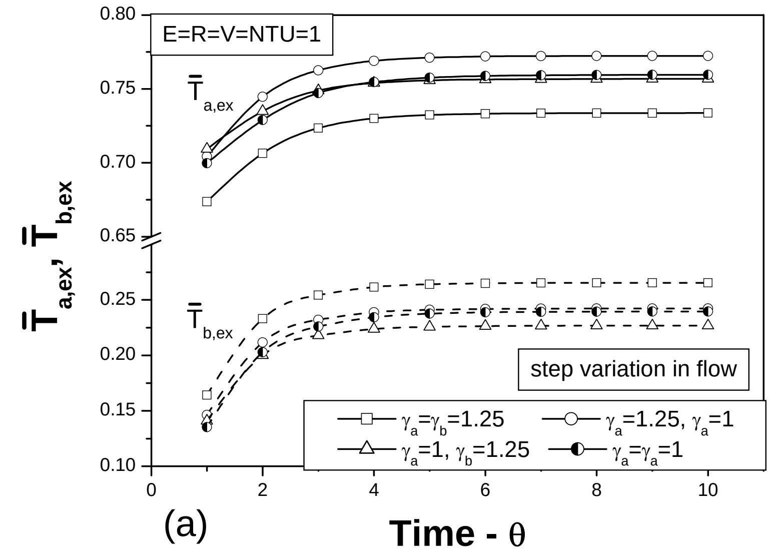
Figure 6 Combined effect of temperature and flow transients for step change in hot fluid inlet temperature for different step variation in fluid flow rates.

Figure 7 Combined effect of temperature and flow transients for (a) step, (b) ramp, (c) exponential, and (d) sinusoidal change in hot fluid inlet temperature with step or ramp change in fluid flow rates.

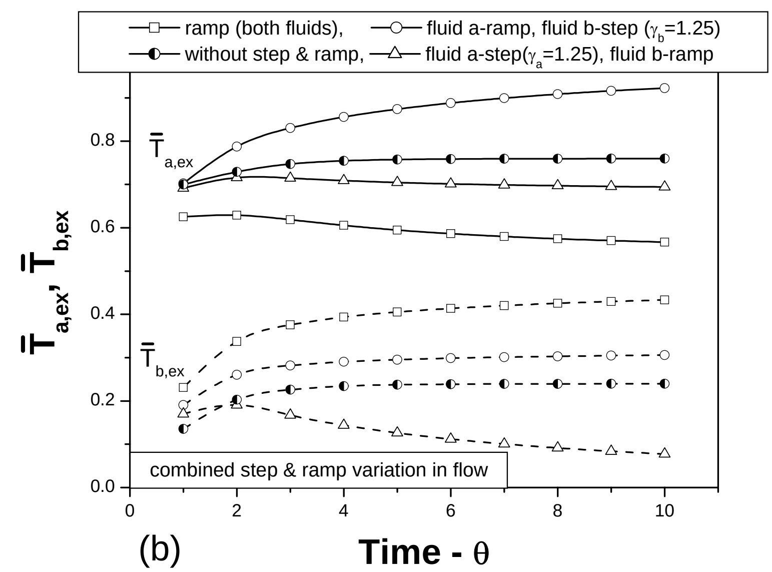

(a)
Fluid b
Fluid a
La
Lb
(b)
D
C
Fluid a
A
B
Separating sheet
with fins
z
y
x
Fluid b



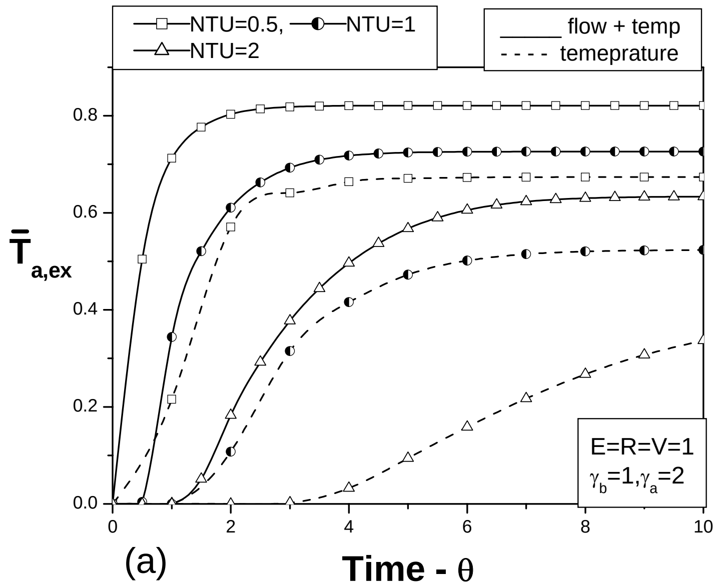
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10
$T_{a,in}$
Hot Fluid
Cold Fluid
Spiga and Spiga [12]
E=R=1, V=λ=0, Pe=inf
NTU=4
NTU=2
NTU=2
NTU=4
$T_{b,in}$
$\bar{T}_{a,ex}$, $\bar{T}_{b,ex}$
Time - θ

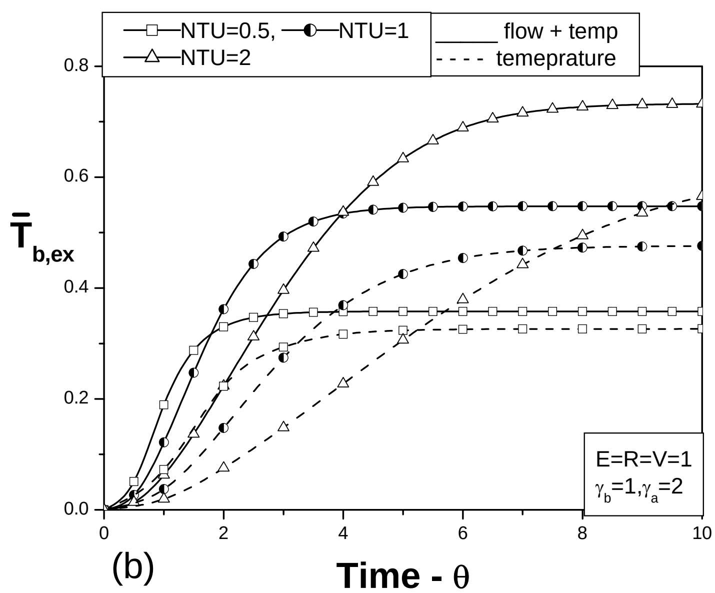

E=R=V=NTU=1
$\bar{T}_{a,ex}$
$\bar{T}_{b,ex}$
step variation in flow
$\gamma_a=\gamma_b=1.25$
$\gamma_a=1.25$, $\gamma_a=1$
$\gamma_a=1$, $\gamma_b=1.25$
$\gamma_a=\gamma_a=1$
$\bar{T}_{a,ex}$, $\bar{T}_{b,ex}$
Time - θ
0.80
0.75
0.70
0.65
0.25
0.20
0.15
0.10
0
2
4
6
8
10

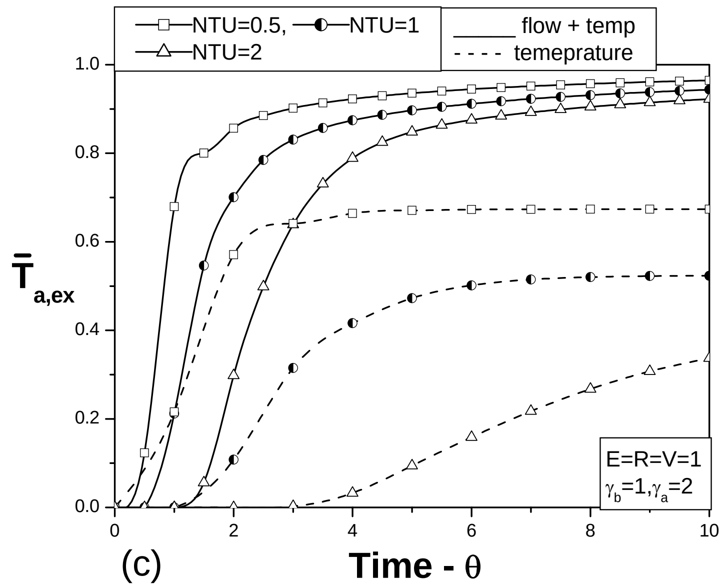
(a)

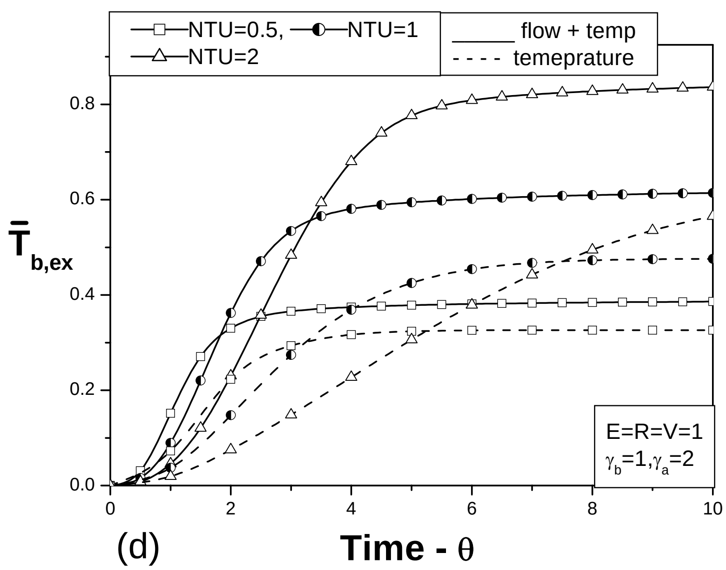

ramp (both fluids),
fluid a-ramp, fluid b-step (γ_b=1.25)
without step & ramp,
fluid a-step(γ_a=1.25), fluid b-ramp
$\bar{T}_{a,ex}$
$\bar{T}_{b,ex}$
combined step & ramp variation in flow
$\bar{T}_{a,ex}$, $\bar{T}_{b,ex}$
Time - θ
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10

(b)

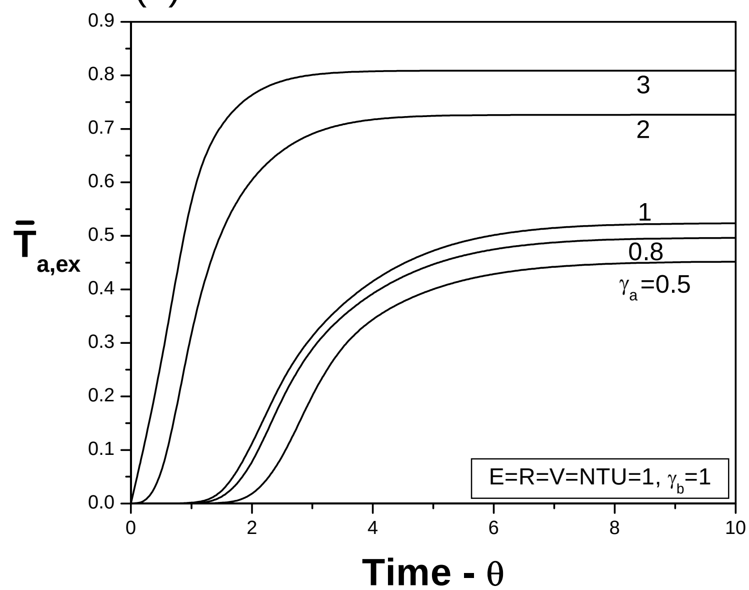

NTU=0.5, NTU=1
NTU=2
flow + temp
temeprature
0.8
0.6
0.4
0.2
0.0
$\bar{T}_{a,ex}$
E=R=V=1
γ_b=1,γ_a=2
0
2
4
6
8
10
(a)
Time - θ


NTU=0.5, NTU=1
NTU=2
flow + temp
temeprature
0.8
0.6
0.4
0.2
0.0
$\bar{T}_{b,ex}$
E=R=V=1
γ_b=1,γ_a=2
0
2
4
6
8
10
(b)
Time - θ

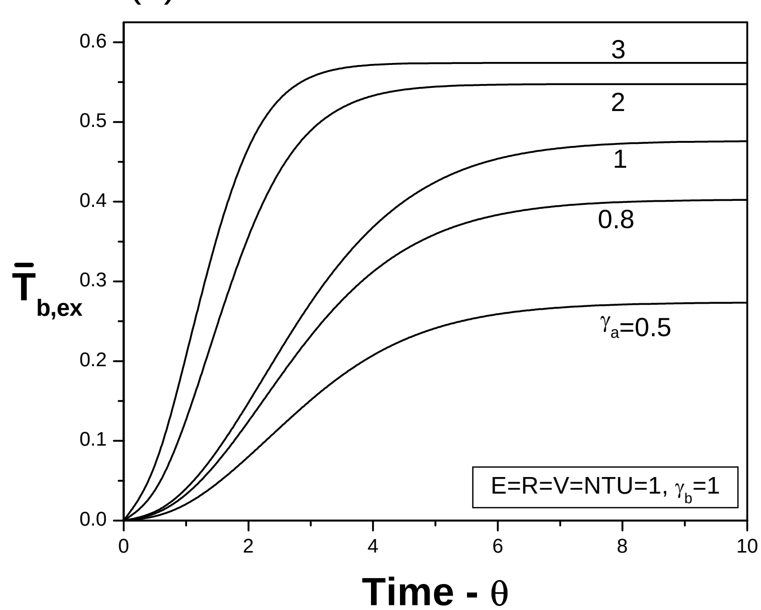

NTU=0.5,
NTU=1
NTU=2
flow + temp
temeprature
E=R=V=1
γb=1,γa=2
T̄a,ex
Time - θ
(c)

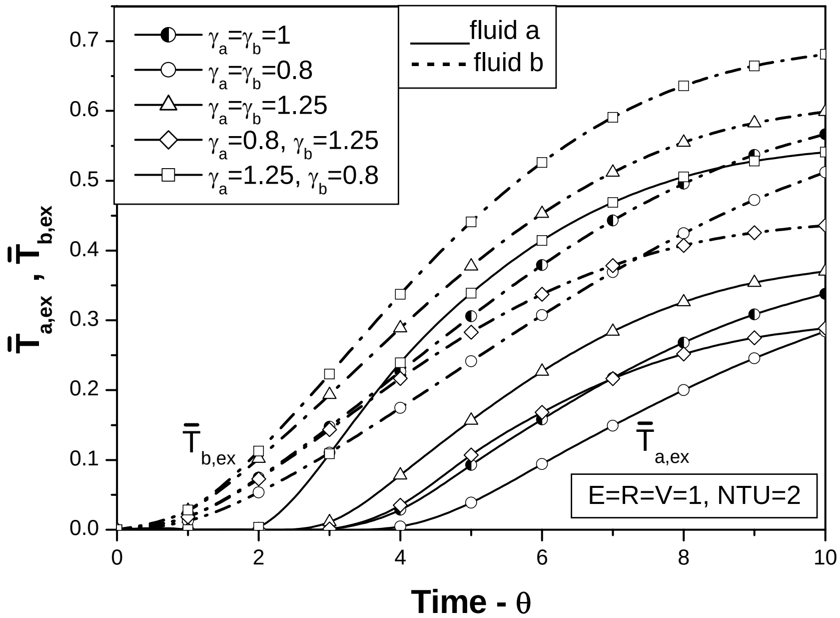

NTU=0.5,
NTU=1
NTU=2
flow + temp
temeprature
E=R=V=1
γb=1,γa=2
T̄b,ex
Time - θ
(d)

(a)

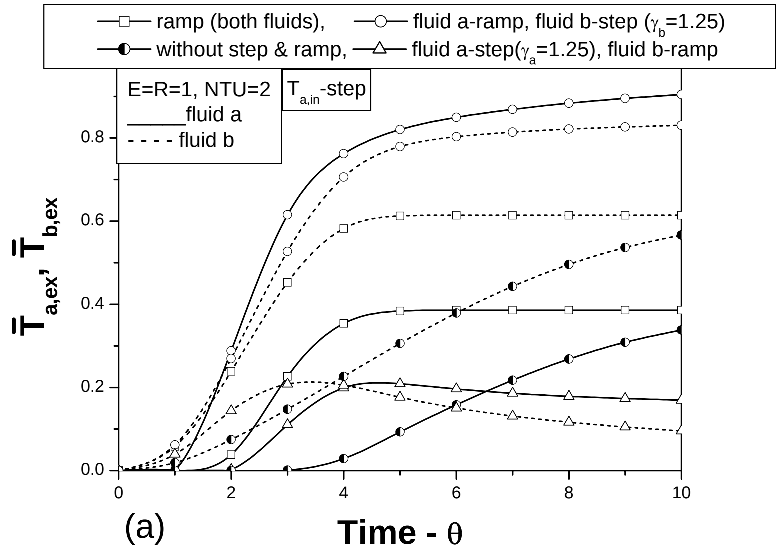

0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
2
4
6
8
10
3
2
1
0.8
γa=0.5
T̄a,ex
E=R=V=NTU=1, γb=1
Time - θ

(b)

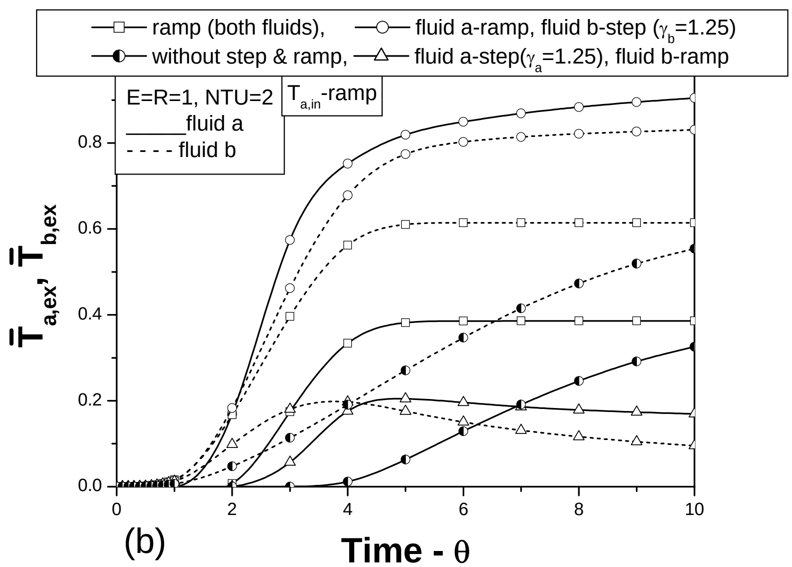

0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
2
4
6
8
10
3
2
1
0.8
γa=0.5
T̄b,ex
E=R=V=NTU=1, γb=1
Time - θ



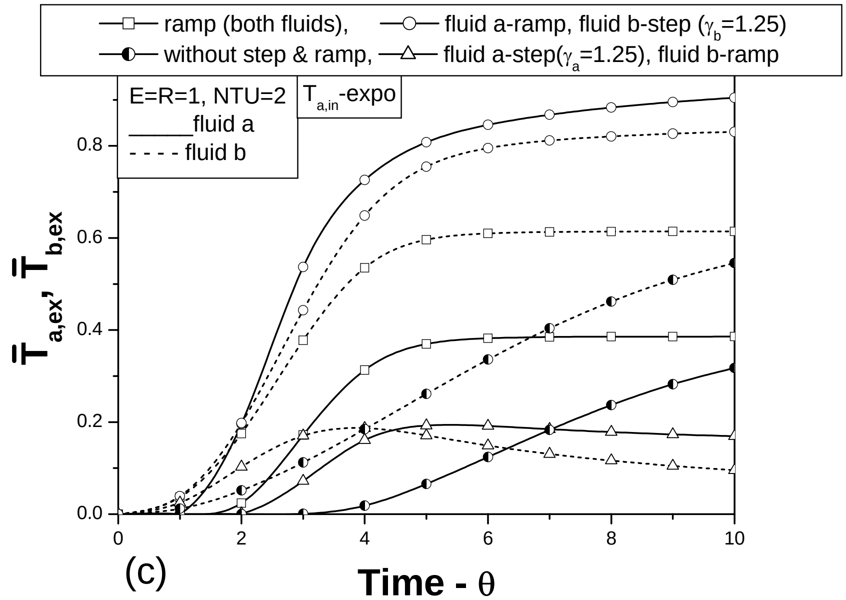
γa=γb=1
γa=γb=0.8
γa=γb=1.25
γa=0.8, γb=1.25
γa=1.25, γb=0.8
fluid a
fluid b
E=R=V=1, NTU=2
T̄b,ex
T̄a,ex
T̄a,ex , T̄b,ex
Time - θ
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
2
4
6
8
10


ramp (both fluids),
fluid a-ramp, fluid b-step (γb=1.25)
without step & ramp,
fluid a-step(γa=1.25), fluid b-ramp
E=R=1, NTU=2
fluid a
fluid b
Ta,in-step
Ta,ex, Tb,ex
Time - θ

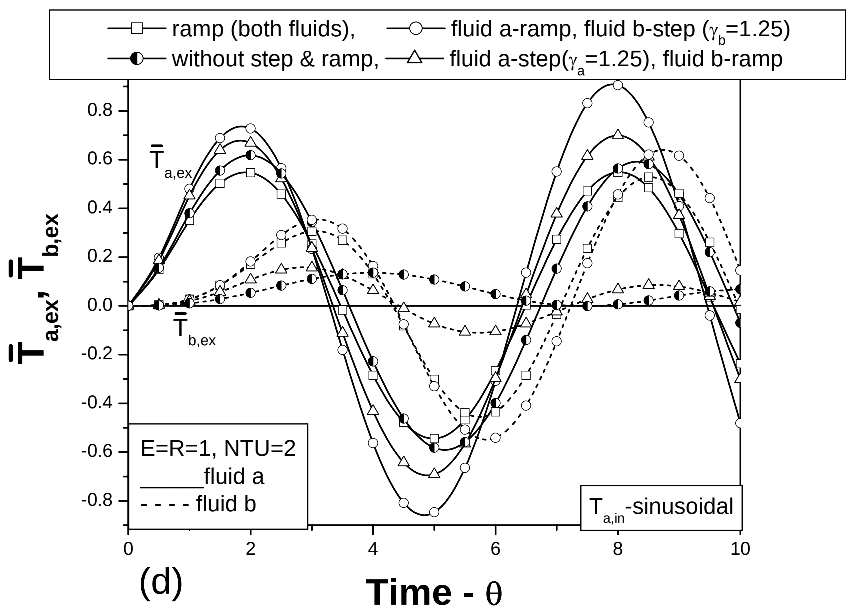
(a)


ramp (both fluids),
fluid a-ramp, fluid b-step (γb=1.25)
without step & ramp,
fluid a-step(γa=1.25), fluid b-ramp
E=R=1, NTU=2
fluid a
fluid b
Ta,in-ramp
Ta,ex, Tb,ex
Time - θ

(b)


ramp (both fluids),
fluid a-ramp, fluid b-step (γb=1.25)
without step & ramp,
fluid a-step(γa=1.25), fluid b-ramp
E=R=1, NTU=2
fluid a
fluid b
Ta,in-expo
Ta,ex, Tb,ex
Time - θ

(c)


ramp (both fluids),
fluid a-ramp, fluid b-step (γb=1.25)
without step & ramp,
fluid a-step(γa=1.25), fluid b-ramp
Ta,ex
Tb,ex
E=R=1, NTU=2
fluid a
fluid b
Ta,in-sinusoidal
Ta,ex, Tb,ex
Time - θ

(d)