Experimental and Theoretical Studies of an Ice Storage Regenerator

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Theoretical and experimental studies of an ice storage system encapsulated with phase change materials in which in the hot period energy is absorbed and in the cold period released, are discussed. An algorithm to solve the coupled partial differential equations for heat transfer and storage in the phase change regenerator on the bed scale and on the phase change material scale is presented. The bed is simulated via the tanks in series approximation. The phase change material scale is solved by Orthogonal Collocation applied to the equations transformed to immobilize the melt/solid interface and eliminate the effect of spherical geometry. Parametric studies show the effects of specific dimensionless group. A phase change material consisting of water in spherical support is used in a lab scale to verify the mathematical model. Experiments with heated or cooled air passing through the system are described. The measured outlet temperature results are compared qualitatively with the model predictions.

INTRODUCTION

Fixed bed thermal regenerators are used to recover, store, and reuse waste energy. Large regenerators have usage in the steel, aluminum, glass making furnaces and waste heat recovery systems particularly for the stack gases [1]. Such systems are cycled between the heat storing and heat releasing modes. First, a stream containing waste heat (e.g., exhaust gas from a boiler or furnace) is passed through the bed where the heat is transferred to the ceramic packing. Later a cold stream (e.g., the fresh air to the boiler or furnace burners) is passed through the hot bed to pick up the heat stored in the matrix. Conventional regenerators utilize the sensible heat of the packing to absorb and release energy.

It has long been recognized that compared to the sensible heat storage, larger amounts of energy per unit volume can be stored by utilizing the latent heat of a phase change. For example, the solid to liquid phase change of Glauber salt which was proposed to store solar energy for domestic heating. In this case, during the daytime hours the incident sunlight shining into the building is stored as the salt melts. Then at nighttime, as the salt solidified, the released energy can heat the building. Recently, latent heat “cold storage” has been proposed as a means of leveling air conditioning loads in hot climates. One scheme, which is being commercialized, uses latent heat to store waste heat from an automobile engine so that it may be used to preheat the engine in cold climates following being off for more than several hours. This minimizes the period of time the engine is warming, a period of time when fuel efficiency is low and tailpipe hydrocarbon emissions are the highest. A large-scale latent heat storage has been proposed for reclaiming high temperature waste energy in the firing of bricks. It is evident that in a typical packed bed regenerator, greater amounts of energy can be stored if the packing were replaced with a phase change materials and stores energy as latent heat. In this case, as some means of containing or supporting the Phase Change Material (PCM) must be provided since the material can flow when it is in the liquid state.

Two approaches are commonly used: a supported PCM and an encapsulated PCM. With a supported PCM, the liquid phase compound is absorbed in an inert porous structure. With an encapsulated PCM, the liquid is contained in a shell of inert material. A regenerator, which utilizes phase change heat storage, is referred to as a Phase Change Regenerator (PCR).

Models for the PCR are complex, involving the solution of the classical Stefan problem for phase change heat storage on the scale of the PCM, coupled with the heat balance equation for the scale of the PCR packed bed. Studies on the phase change heat storage have been conducted in many different areas. Armilli and Graves [2] present calculations for a PCR filled with spherical PCM. A supported PCM is modeled, composed of a porous matrix filled with a phase change alloy. The model presented accounts for the convection, heat accumulation in the fluid, heat losses through the wall of the PCR, and energy storage by PCM. The model also assumes that there is no radial temperature gradient, yet a wall heat loss term is included. The coupled equations for the Stefan problem (PCM scale) and the bed scale were solved by an iterative finite difference scheme. Results were reported for only a single case: heat recovery from combustion gases. No parametric studies were investigated.

Chen and Yue [3] have investigated cold storage in a PCR, which is packed with porous spheres holding water. They developed a lumped parameter model, which assumes that the PCR is in a pseudo steady state, and changes as ice is formed. The PCR is depicted as a single, well-stirred tank; dispersion in the bed and heat conduction within the PCM was neglected. Experiments were performed using a 100 mm diameter by 260 mm long bed packed with 34 mm OD spheres. The film heat transfer coefficient was estimated by fitting the model to the experimental data.

The model compared favorably with the experimental data only with latent heat storage and badly under predicted the fluid outlet temperature when storage was by sensible heat only. Chen and Yue [3] argue that the reason for this discrepancy is that their model assumes a constant film heat transfer coefficient, when in fact the film coefficient is not constant. In their paper, Chen and Yue [3] showed that a plot of temperature distribution at different positions within their experimental PCR in which the dimensionless temperature changes by a factor of five between the inlet and outlet of the bed. Since the model is force fitted to match the outlet temperature by estimating a value of the heat transfer coefficient, at times when the gradient within the bed is constant (during latent heat storage) the lumped parameter model predicts the data trend. When the gradient within the bed changes (as during sensible heat storage) the model cannot predict the data trend.

The aim of the present work is to develop a versatile mathematical model for the simulation of a laboratory scale phase change regenerator system and to study the parametric effects on the thermal performance of the system.

PCR MODEL

The information obtainable from a complete and acceptable PCR model consists of (1) the thermal efficiency; (2) the temperature-time history of outlet fluid; (3) the temperature profile through the bed; (4) the temperature profile within an individual PCM at a selected location; and (5) position of the solid-liquid interface within a PCM. The model equations presented below are based upon the following assumptions; no radial temperature gradients on the bed scale; no radiation heat transfer on either scale; constant physical and thermal properties for the liquid and solid states; the PCM is in a spherical shape, supported one and in a single phase at the start of the operation.

A logical discretization scheme for the axial dispersion equation is to invoke the cells-in-series approximation, which is shown in [4] to be equivalent to a central finite difference approximation of the axial dispersion equation. The bed is modeled as a collection of N well-mixed tanks (cells) in series. The dimensionless temperature is defined as;

$$T = \frac{(t_{i,h} - t)}{(t_{i,h} - t_{i,c})} \tag{1}$$

The symbols $t_{i,h}$ and $t_{i,c}$ represent the inlet fluid temperatures during the heating (energy storing) and cooling (energy releasing) periods respectively. The accumulation parameter ψ (ratio of the sensible heat of the fluid in the bed to that of the packing) is defined as

$$\psi = \frac{\varepsilon \rho_f C_f}{(1-\varepsilon)\rho_p C_p} \tag{2}$$

Where, ε is the bed porosity, ρ_f and ρ_p are the densities of the fluid and the packing, respectively, C_f and C_p are the heat capacities of the fluid and packing, respectively.
The Stefan number (ratio of PCM sensible heat to latent heat) is obtained from;

$$Ste = \frac{C_{PCM}(t_{i,h} - t_{i,c})}{\lambda} \tag{3}$$

Where, C_{PCM} is the heat capacity of the PCM, and λ is the latent heat of the pure phase change compound.
The bed scale equation in non dimensional form will be rearranged as;

$$\psi \frac{\partial T_{f,n}}{\partial \vartheta} = N(T_{f,n-1} - T_{f,n}) - St(T_{f,n} - T_{PCM\,1}); \qquad 1 \le n \le N \tag{4}$$

Where $T_{PCM\,1}$ represents the temperature at the outer surface of the PCM in the mixing cell defined as $T_{PCM,1} = \frac{t_{i,h} - t_{PCM,1}}{t_{i,h} - t_{i,c}}$, and ϑ is the non-dimensional time coordinate which is defined by;

$$\vartheta = \psi \frac{v_f}{\varepsilon L} \tau \tag{5}$$

With, τ is the actual time, L is the length of the bed, and v_f is the fluid superficial velocity. The Stanton number for heat transfer (ratio of film convection to fluid convection in the bed) is defined as:

$$St = \frac{3(1-\varepsilon)hL}{R_{PCM} v_f \rho_f C_f} \tag{6}$$

Where, h and R_{PCM} are the convective heat transfer coefficient and PCM radius respectively. The boundary condition at the inlet is:

$$T_{f,0} = T_{inlet} = \frac{t_{i,h} - t_{inlet}}{t_{i,h} - t_{i,c}} \tag{7}$$

The classical Stefan problem which, is solved on the PCM scale for this situation is given by two PDEs of the form:

$$\frac{1}{\varphi^2} \frac{\partial}{\partial \varphi}(\varphi^2 \frac{\partial T_y}{\partial \varphi}) = \frac{3Bi}{St} \frac{\partial T_y}{\partial \vartheta}; \qquad \omega_{x,y,i} \le \varphi \le \omega_{x,y,o} \tag{8}$$

Where, φ is the dimensionless, radial coordinate in the PCM sphere ($\varphi = \frac{r}{R_{PCM}}$) ranging from 0 at the center to 1 at the outer radius, T_y is the y-phase temperature and Bi is the Biot number for heat transfer, defined as

$$Bi = \frac{hR_{PCM}}{k_{PCM}} \tag{9}$$

Where, k_{PCM} is the effective thermal conductivity of the PCM. The terms $\omega_{x,y,i}$ and $\omega_{x,y,o}$ are the endpoints, where the subscript x is replaced by c in a cooling period and h in a heating period, the subscript y is replaced by s for solid phase and l for liquid phase, and the subscript i and o represent inner and outer endpoints of the domain. Values of ω are defined as;

$$\begin{aligned} &\omega_{h,s,i} = 0; \omega_{h,s,o} = \delta_d; \omega_{h,l,i} = \delta_d; \omega_{h,l,o} = 1 \\ &\omega_{c,l,i} = 0; \omega_{c,l,o} = \delta_d; \omega_{c,s,i} = \delta_d; \omega_{c,s,o} = 1 \end{aligned} \tag{10}$$

Where, δ_d is the solid-liquid interface position within the PCM. The boundary conditions (BCs) for two PDEs are:

$$\varphi = 0; \frac{\partial T_{yi}}{\partial \varphi} = 0 \qquad \text{And} \qquad \varphi = \delta_d; T_s = T_l = T_m \tag{11}$$

$$\varphi = 1; \frac{\partial T_{yo}}{\partial \varphi} = Bi(T_f - T_{yo})$$
(12)

Where T_m is the PCM melting point defined as $T_m = \frac{t_{i,h} - t_m}{t_{i,h} - t_{i,c}}$ and for a heating period yi = s, yo = l and for a cooling period yi = l, yo = s.

Note

$T_{PCM} = T_{yo}[\varphi = 1]$

The initial condition is:

$$\vartheta = 0; 0 \le \varphi \le 1; T_{yo} = T_{ambient} \tag{13}$$

The position δ_d is given by an energy balance at the solid-liquid interface:

$$\frac{\partial T_s}{\partial \varphi} - \frac{\partial T_l}{\partial \varphi} = \frac{3}{St}\frac{Bi}{Ste}\frac{\rho_{PC}}{\rho_{PCM}}\frac{d\delta_d}{d\vartheta}; \varphi = \delta_d \tag{14}$$

We next consider how the Stefan problem should be discretized. Due to the spherical geometry, the solution to the Stefan problem is nonlinear in position as δ_d approaches the center of the PCM.

Indeed, analytical solution to the classical problems involving this geometry is often solved by transforming the Stefan nonlinear problem into one of the linear flow [5] (i.e., into slab coordinates). To tackle the problem, a new transformed parameter in the shell surrounding the core is defined as:

$$T_{sh}^{s} = \varphi T_{sh} \tag{15}$$

Where the subscript *sh* corresponds to the shell phase condition (liquid and solid during the heating and cooling periods respectively). Note that the core phase need not be transformed since the boundary conditions force the solution to be smooth and easily approximated by low-order polynomials.

We define the immobilized coordinate system for the core and shell phases respectively ζ_{co} and ζ_{sh} each of which span [0, 1] by:

$$\zeta_{co} = \frac{\varphi}{\delta_d} \tag{16}$$

$$\zeta_{sh} = \frac{\varphi - 1}{\delta_d - 1} \tag{17}$$

The PDEs of the Stefan problem are converted into a series of ODEs by discretization of the spatial coordinates. Orthogonal collocation is used as discussed by [6] and [7].

The complete model is thus solved numerically by integrating in time for each of the N stages in the regenerator the ODEs, as well as by associated boundary and initial conditions. Each stage is solved independently, starting from $\vartheta = 0$ to the ending time. Then, the next cell is solved, thereby marching cell by cell along the regenerator. The output from a cell is stored in an array and cubic sp-lines are used to approximate the temperature history so that it could be used as input for the next mixing cell.

SIMULATION RESULTS

The effects of the parameters such as T_m, Ste, St, Bi, ψ were investigated in this study. Figure 1 shows the effect of T_m on the fluid temperature history for the heating and cooling periods. For low values of T_m, in the heating period, the breakthrough time is shortened. As the PCR becomes more non ideal, the length of the constant temperature zone is also reduced. However, there always is some zone, albeit small in duration (length), where the response moves through a temperature T_m .When this zone becomes sufficiently small, it represents an inflection point in the response. Of course, when this happens, the PCR is not operating efficiently in the sense of the second law.

Effect of Ste***:*** The Stefan number is the ratio of sensible heat to latent heat of the PCM. As this number tends to infinity (Ste $\rightarrow \infty$), sensible heat storage dominates, while when Stefan number approaching zero (Ste $\rightarrow 0$), latent heat storage dominates. For optimal PCR operation, the latter limiting case is preferred , since this means that there is a great amount of latent heat which can be stored(relative to sensible heat). However, physical properties of useful phase change compounds and usable temperature ranges generally limit Ste to O(10^{-2}) .The practical upper limit on Ste is O(1), since larger values of Ste would mean that the amount of sensible heat is much higher than the latent heat. These effects are clearly observed from Figure 2.

Effect of St: The Stanton number is defined as the ratio of inter-phase heat transfer by film convection to inter-phase heat transfer by bulk flow convection.

It is a gauge of the relative importance of convection on each of the length scales. Generally St ranges between 0.5 and 300, depending upon the working fluid phase, the physical properties, and the fluid flow rate through the bed. As $\mathrm{St} \rightarrow \infty$, the PCR becomes close to ideal condition, since the characteristic time for heat transfer by bulk convection is much greater than the characteristic time for heat transfer by film convection around the PCM. The effect of St can be seen in Figure 3, which shows a series of responses (with St as the parameter) for the heating period (Figure 3a) and the cooling period (Figure 3b). For a value of St of 10, the PCR performance is approaching the ideal case, while for a value of 5 the performance is deviating from the ideal condition. For the non ideal PCR the outlet temperature is greater than T_m for a cooling period and less than T_m in a heating period, since the energy in the fluid cannot be transferred to/from the PCM fast enough.

Effect of Bi: The Biot number is defined as the ratio of heat transfer rate by convection in the film surrounding the PCM to the heat transfer rate by conduction in the PCM. Generally, Bi can range between 0.1 and 100 depending upon the value of the convective heat transfer coefficient. As Bi increases, the rate of heat supply to the PCM increases. When this happens, the rate of heat supply to the PCM is greater than the rate of heat conduction in the PCM, so heat cannot be stored at a fast enough rates. Figure 4 shows this effect upon the temperature response. As illustrated in the figure when Bi decreases from 20 to 0.1, the response begins to resemble that of the ideal PCR. This effect is evident in both the heating period, Figure 4a, and also in the cooling period, Figure 4b. From Eq. (8), it is obtained that rather than the Biot number itself, a more meaningful measure of the non ideality of the PCR caused by PCM thermal conduction is the ratio of the Bi and St. The term (3Bi/St) in Eq. (8) is the ratio of heat transfer by bulk convection in the bed to heat transfer by conduction in the PCM. Therefore, as the characteristic time for heat transfer in the PCM becomes smaller, relative to the characteristic time for heat convection along the bed, the PCR becomes more efficient at storing heat and thereby approaches the ideal PCR. Thus, as $(3\mathrm{Bi}/\mathrm{St}) \rightarrow 0$ the PCR becomes more ideal.

Effect of ψ: The accumulation parameter is the ratio of the volumetric heat capacity of the fluid to that of the PCM. The value of ψ is O (10^{-3}) when the fluid passing through the PCR is a gas and O (1) when the fluid is a liquid. From the definition of ψ , it is apparent that ψ should affect the fluid temperature history by changing the velocity of the temperature front through the bed. The latent heat contribution is significantly larger than ψ. However as ψ increases, the entire response curve is shifted forward to longer times, since the onset of the response is governed by the passage of the first front (the sensible heat front) through the bed. These effects are illustrated in Figure 5.

PCR EXPERIMENTS

An experimental, lab-scale, low-temperature PCR was built to test the mathematical model. Only a brief description of the test PCM and PCR will be presented here. A supported PCM was made from polypropylene filled with distillated water in the spherical balls of 37 mm OD and 0.5-m wall thickness. Figure 6 shows a schematic diagram of experimental setup. The bed container is a PVC tube 100 mm in ID, 5mm in wall thickness and 260 mm in length. Two thermocouples were affixed to the outside of the bed container.

The PCM is confined in the tube by two porous distributor plates at the ends of the tube. These distributor plates with 2 mm thickness were made from porous polypropylene, 0.15 mm average pore size. The thermocouple leads are sealed to the outer surface of the porous plate. Each distributor disk is held in an O-ring sealed holder, machined from PVC which slips snugly into the bed container tube. The bed filled

with PCM and capped at both ends with the thermocouple-embedded distributor plates, was centered in the partials tubes.
Temperature measurements from the inlet and outlet of the PCR were recorded by a simple data acquisition system consisting of a measurement unit with two thermocouple slots. The measurement accuracy was in the order of $0.01\,^{\circ}$C.

CONCLUDING REMARKS

With the importance of heat recovery systems to reduce energy consumption, there is a need to develop an understanding of the PCR operation. A comprehensive computational scheme was presented for the prediction of the temperature histories of the system. The PCM scale is modeled successfully by appropriate transformations, immobilizing the moving boundary and discretizing via orthogonal collocation. The numerical solution of the model equations is done efficiently and accurately with minimal computer resources and time. Simulations can be used to predict temperature profiles within the bed and the outlet fluid temperature. Parametric studies have verified that for all practical purposes, the ideal PCR is approached for: (3Bi)/St$< 5*10^{-3}$; Pe>40; St>50; Ste$<10^{-1}$; and $\psi \geq 1$.

The computational model which was developed is comprehensive and robust. It is capable of assessing the effect of operating and design parameters and performance of commercial-size PCRs.
As it stands, the model solved by the developed numerical algorithm, is a useful tool for predicting thermal response for large-scale adiabatic PCRs.

NOMENCLATURE

$A_i\,(i = 1,2,3)$ = coefficients used in Eq. 18
Bi = Biot number (Eq. 9)
C = heat capacity, *kJ/kg. K*
h = convective heat transfer coefficient, W/m^2 K
k = thermal conductivity, W/m.K
L = bed length, m
N = number of cells
R = radius, m
St = Stanton number (Eq. 6)
Ste = Stefan number (Eq. 3)
t = temperature, K
T = dimensionless temperature (Eq. 1)

Greek letters

δ_d = solid-liquid interface position, m
ζ = dimensionless immobilized coordinate (Eq.16 and 17)
ω = domain endpoint (Eq.10)
λ = latent heat, kJ/kg
τ = actual time, s
ϑ = non dimensional time coordinates (Eq. 5)
φ = dimensionless radius, $\varphi = \dfrac{r}{R_{PCM}}$
ψ = accumulation parameter (Eq. 2)
ε = voidage
v_f = fluid superficial velocity, m/s

ρ = density, kg/m^3

Subscripts

co = core phase
c = cold stream or cooling period
dp = distributor plate
f = fluid
h = hot stream or heating period
i = inlet or inner
l = liquid phase
m = melting point
n = stage number
o = outlet or outer
PCM= PCM property
p = packing
s = solid phase
sh = shell phase
x= generic for h and c
y = generic for s and l
yi = generic for inner phase s and l
yo= generic for outer phase s and l

Superscripts

s = modified shell phase

Acronyms

BC = boundary condition
ODE = ordinary differential equation
PC = phase change component
PDE = partial differential equation
PCR = phase change regenerators
PCM = phase change materials

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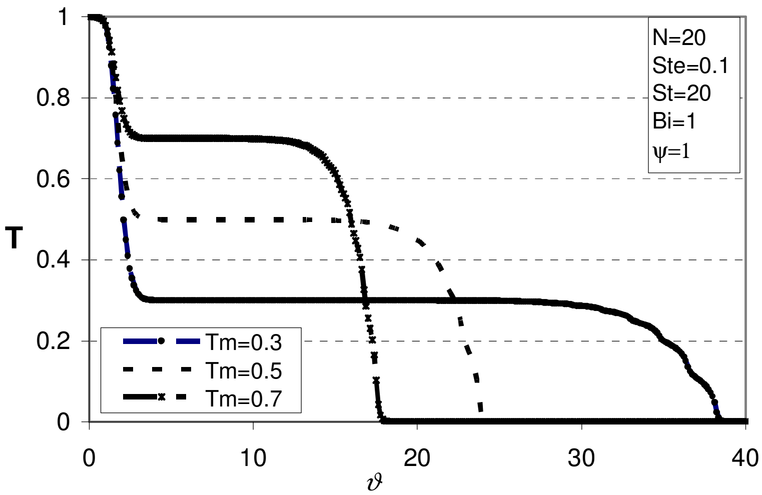

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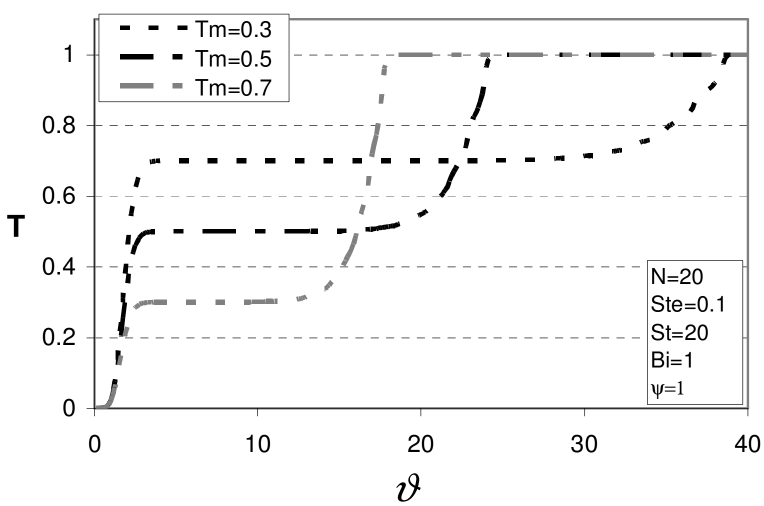
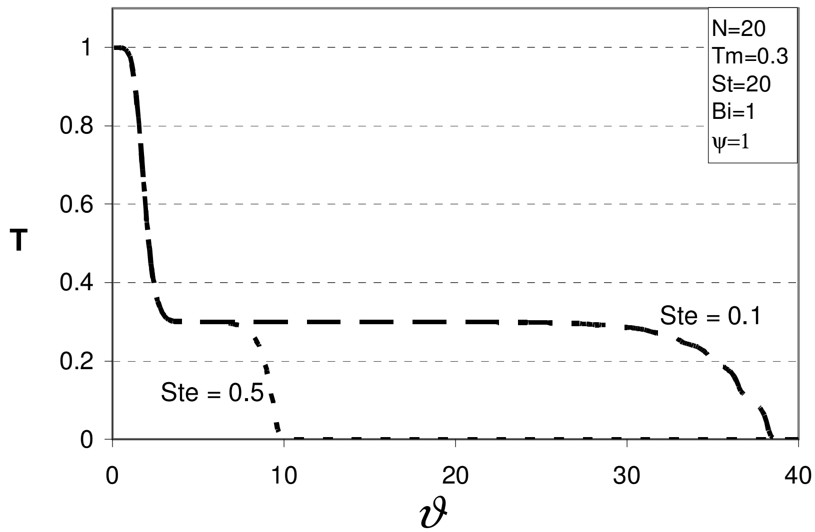


(b)

Figure 1 Effect of T_m on the fluid temperature history.

(a) Heating period; (b) Cooling period



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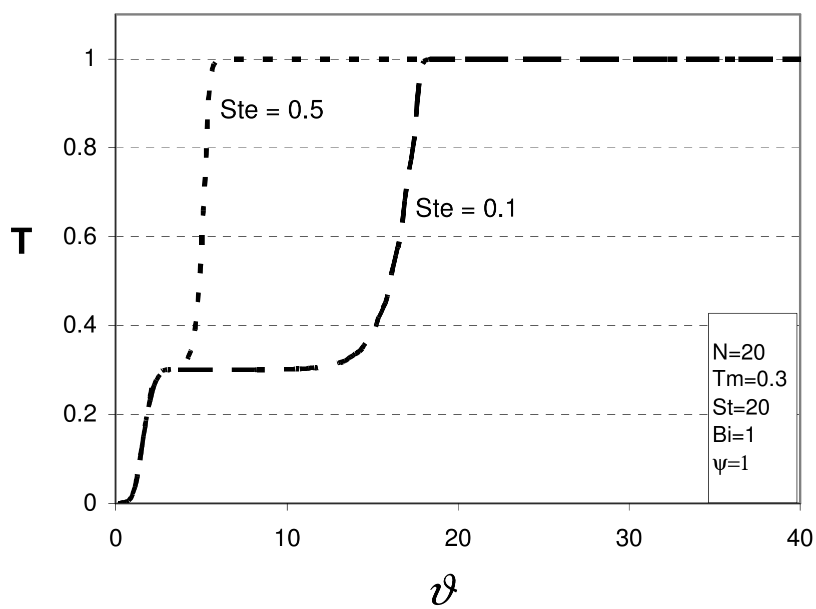
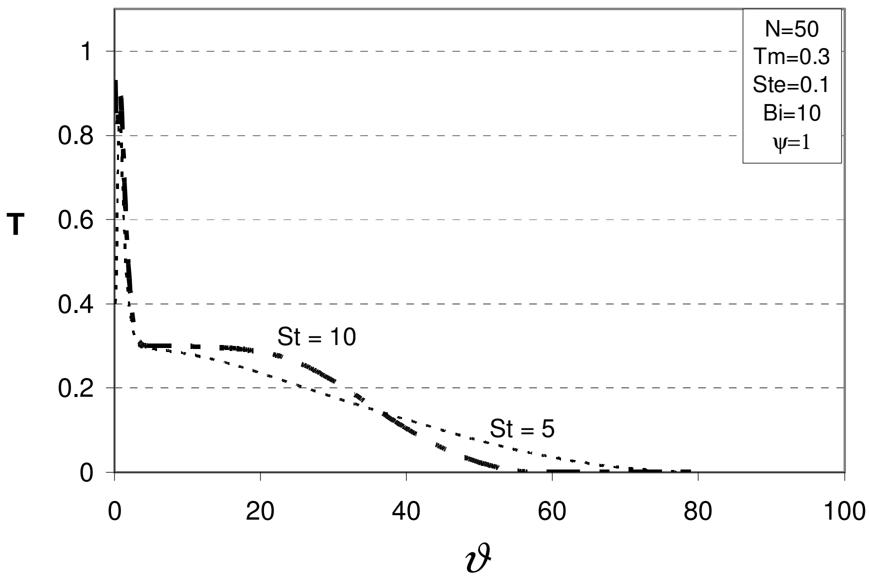


(b)

Figure 2 Effect of Ste on the fluid temperature history.

(a) Heating period; (b) Cooling period.



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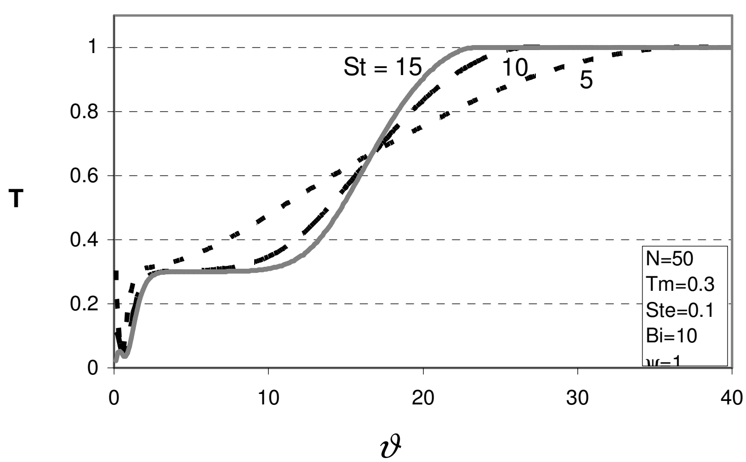
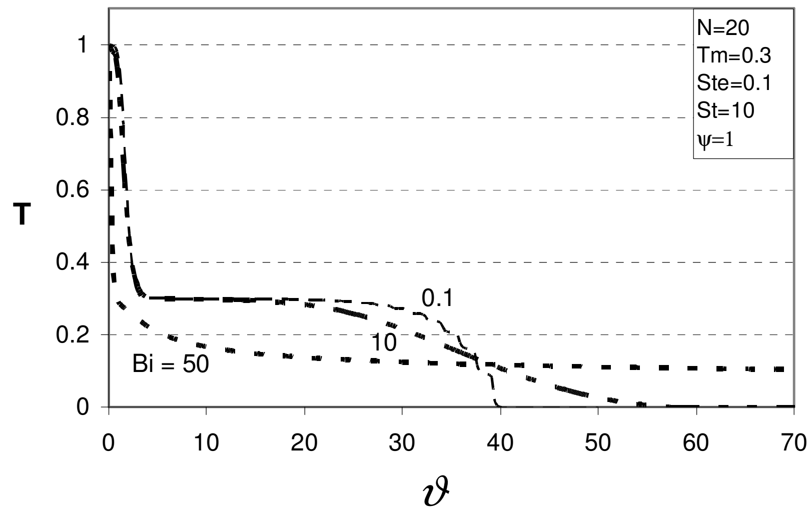


(b)

Figure 3 Effect of St on the fluid temperature history.

(a) Heating period; (b) Cooling period



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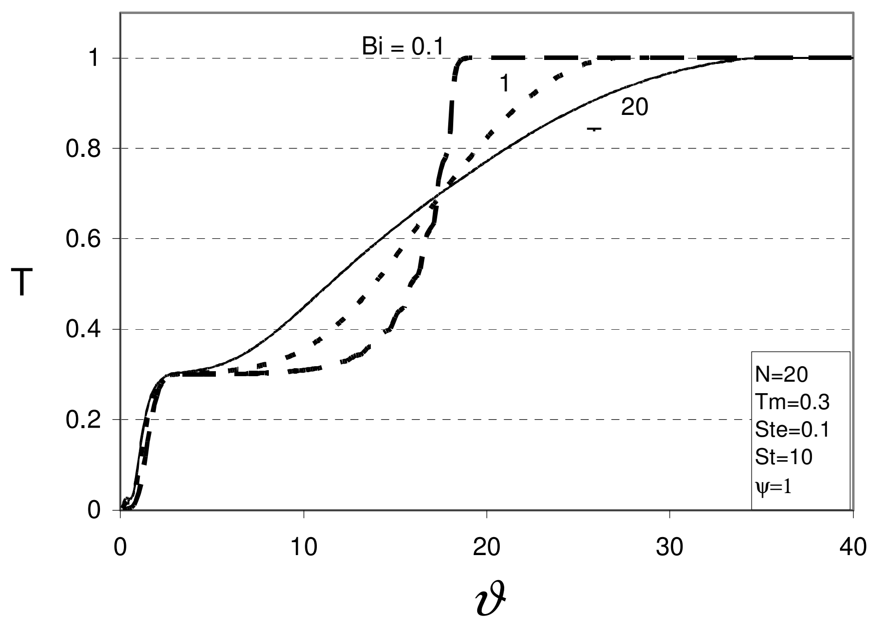
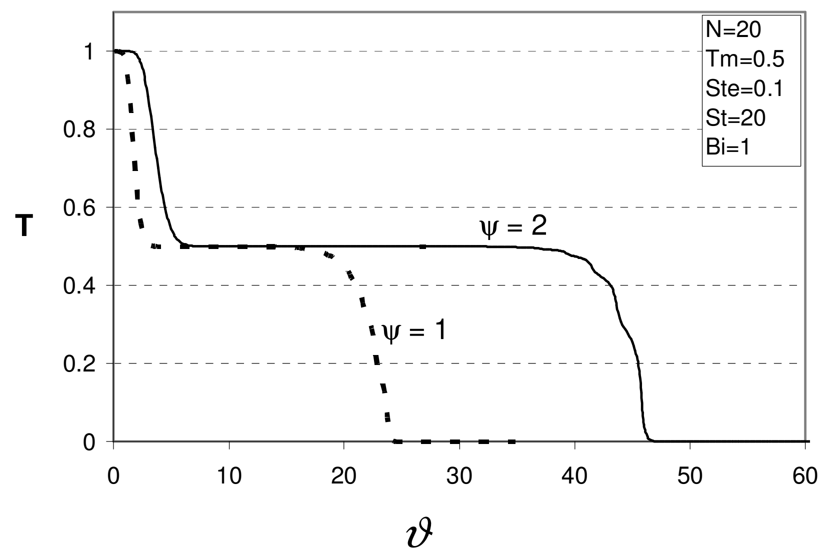


(b)

Figure 4 Effect of Bi on the fluid temperature history.

(a) Heating period; (b) Cooling period.



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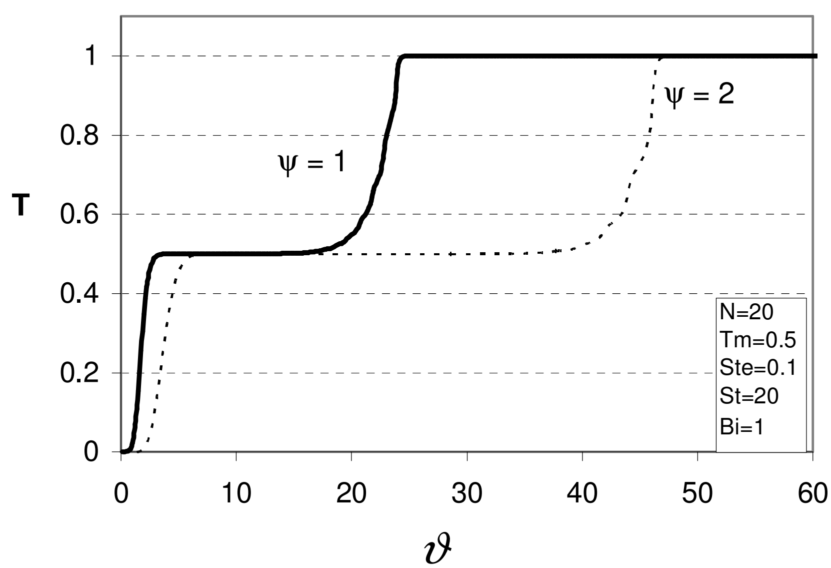

(b)

Figure 5 Effect of ψ on the fluid temperature history.

(a) Heating period; (b) Cooling period.

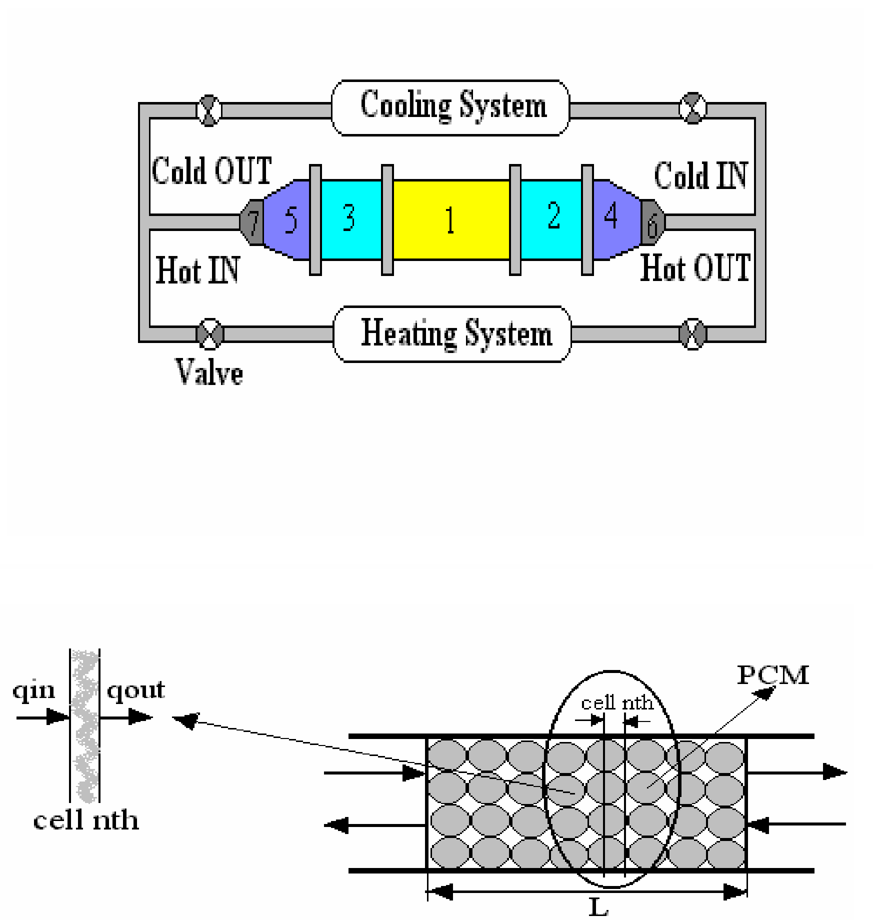

Figure 6 Schematic diagram of experimental setup