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A MODEL OF DIRECT CONTACT HEAT TRANSFER FOR LATENT HEAT ENERGY STORAGE

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Abstract

Direct contact heat transfer is an attractive method to reduce the cost of heat exchange for latent heat thermal energy storage systems. However, current performance information is insufficient to allow an accurate appraisal of its economic and technical feasibility. In a direct contact heat transfer system, an immiscible fluid is bubbled through the storage media and heat is transferred between the phases as the droplets rise. In this paper, an analytical model is presented for predicting the temperature of the rising droplets from information in the literature. The drop size is calculated from empirical correlations in the jetting formation region and rise velocity is characterized by a creeping-flow free-surface cell model which accounts for the hindering effects of neighboring droplets. The viscosity of the crystallizing solution in the rise velocity equation is approximated by an expression for concentrated suspensions, where the percentage of solids is taken as the percentage of crystallization. Dispersed phase holdup is predicted iteratively with the rise velocity. Calculation of the rate of heat transfer to the dispersed immiscible fluid droplets is based on three different internal hydrodynamic approximations: rigid, internally circulating, and well-mixed spheres. The predictions of the circulating drop case agree reasonably well in the latent heat region with previous data on a similar system. However, because the model is also sensitive to the estimates used for drop size, continuous phase viscosity, and interfacial tension, the heat transfer mechanism cannot be conclusively identified, and experimental research is required to establish the validity of the model.

Nomenclature

a	drop radius
A	drop surface area
A_c	cross-sectional area of column
C_p	specific heat capacity
d_D	mean drop diameter
d_{jn}	jet diameter at point of breakup
d_o	orifice diameter
D	drop diameter
h_c, h_d	continuous and dispersed phase heat transfer coefficient
H	column height
$\dot{m}$	immiscible fluid mass flow rate
Nu_c, Nu_d	continuous and dispersed phase Nusselt number
Pe_c, Pe_d	continuous and dispersed phase Peclet number
Q	volumetric orifice flow rate
Q_{at}	atomization orifice flow rate
Q_{ex}	heat transferred to storage media
Q_{jet}	jetting orifice flow rate
Q_{max}	maximum area orifice flow rate
Q_{vd}	dispersed phase volumetric flow rate
R	drop radius
R_1	container heat loss resistance
T_a	ambient temperature
T_c	continuous phase temperature
T_i	average inlet fluid temperature
T_o	average outlet fluid temperature
U	overall heat transfer coefficient
U_{ens}	drop ensemble terminal velocity
U_n	nozzle velocity
U_{nm}	minimun drop size nozzle velocity
V	drop volume
V_c	total continuous phase volume
α_c, α_d	continuous and dispersed phase thermal diffusivity
γ	surfactant retardation coefficient
θ	residence time
μ	viscosity of concentrated suspension
μ_o	liquid melt viscosity
μ_c, μ_d	continuous and dispersed phase viscosity
$\Delta\rho$	density difference between phases
ρ_c, ρ_d	continuous and dispersed phase density
σ	interfacial tension
ϕ	dispersed phase volumetric holdup
ϕ	solids fraction
ϕ_{max}	maximum attainable solids fraction

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Introduction

Latent heat storage materials undergoing a solid-liquid phase change provide high volumetric energy storage densities over a narrow temperature range. Conventional latent heat storage methods rely on the container material for heat exchange, and heat transfer is impeded by the buildup of a crystallizing solid material on the heat exchanger surface during extraction of energy from storage. To supply an adequate rate of heat transfer through the frozen layer, a high ratio of surface area to volume is required for the combined storage container and heat exchanger. The cost of these units can be substantial.

One solution to this problem is to employ inexpensive container materials such as plastics for low-temperature storage. Alternatively, direct contact heat exchange can be used. Etherington[1] originally proposed this concept for use with latent heat energy storage systems. In a direct contact device, an immiscible fluid is dispersed through the storage media and heat is transferred directly across the phase boundary as the droplets rise (see Fig. 1). The immiscible fluid material also agitates the latent heat material, so that phase segregation is minimized. Direct contact systems have the potential advantage over systems using plastic containers for heat exchange in that they are applicable over a wide range of temperatures.
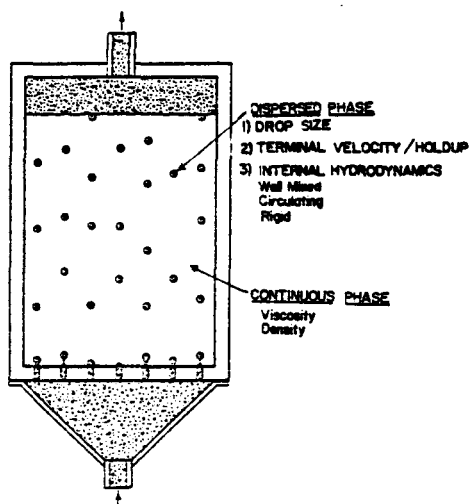
Fig. 1. Parameters controlling heat transfer in direct contact latent heat energy storage.

Heat transfer in direct contact devices has typically been analyzed in terms of volumetric heat transfer coefficients. However, further knowledge of the critical parameters controlling the system is required for accurate design and performance evaluation of such systems. It is desirable to base the analysis on fundamental information, so that it is not restricted to a particular system geometry or selection of materials. The objective of the work described in this paper is to test predictions of direct contact heat transfer based on available information against existing data and determine areas requiring further experimental and analytical research. Estimates of the controlling physical parameters are based on an elementary treatment of information in the literature obtained for related systems.

Modeling Parameters

The parameters controlling the thermal behavior of the dispersed phase immiscible fluid are drop size, terminal rise velocity, and internal droplet hydrodynamics (see Fig. 1). Furthermore, these parameters are a function of varying physical properties, such as viscosity, interfacial tension, and density. A model based on these variables has been developed to predict the temperature of the rising immiscible fluid droplets.

Drop Size

Prediction of the interfacial area formed is necessary to quantify heat transfer rates in direct contact processes. The formation of drops occurs as a fluid is dispersed through a nozzle or an orifice into a second immiscible fluid. The mechanism of drop formation is a function of continuous and dispersed phase fluid properties, flow rate, and orifice characteristics. Several regimes of drop formation have been defined as shown in Fig. 2. Drop-size correlations have been developed for the nonjetting region, the jetting region, and the atomization region.
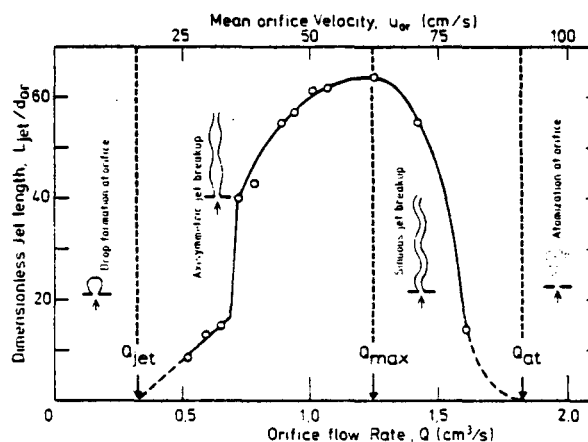
Fig. 2. Typical drop formation regimes.[2]

At low flow rates, drops form directly at the orifice surface, grow, detach, and rise. Scheele & Meister[3] developed a correlation for predicting the drop volume at low injection velocities using a force balance analysis. As the orifice flow rate Q increases, a critical flow Q_{jet} is reached (see Fig. 2), above which a jet of fluid issues from the orifice. The transition exit velocity from single drop formation to jet injection is predicted by Lehrer's equation[4]:

$$U_n = \left[\left(\frac{0.3 u_d g d_0}{\sigma} \right)^2 + \frac{3\sigma}{\rho_d d_0 \left[1 + d_0 (\Delta \rho g / 2\sigma)^{1/2} \right]} \right]^{1/2} - \left(\frac{0.3 u_d g d_0}{\sigma} \right) . \tag{1}$$

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The size of drops resulting from the formation and breakup of liquid jets is not uniform and prediction of mean droplet diameter is difficult. Between flow rates of Q_{jet} and Q_{max}, jet breakup occurs by axisymmetric amplification of surface disturbances known as Rayleigh instability. The jet length increases to a maximum value at Q_{max} and the jet disintegrates into drops of uniform size. At flow rates between Q_{max} and Q_{at} the jet length decreases again and drop formation results primarily from growth of asymmetric instabilities.

Drop size in the jetting region has been calculated using empirical relationships. Below the critical nozzle velocity U_{nm}, at which drops assume a minimum size, the following empirical equation for drop size d_D is suggested by Horvath, Steiner, and Hartland[5]:

$$\frac{d_D}{d_{jm}} = \frac{2.06}{U_n/U_{nm}} + 1.47 \ln \left(U_n/U_{nm} \right) , \qquad (2)$$

where d_{jm} equals the critical velocity jet diameter at the point of breakup and U_n equals the velocity in the nozzle. For the jetting region above the critical velocity, Skelland and Huang[6] give an equation correlating results of six liquid-liquid systems with no mass transfer, using five different nozzle sizes:

$$\frac{d_D}{d_{jm}} = 2.6051 - 0.7747 \left(\frac{U_n}{U_{nm}} \right) + 0.3994 \left(\frac{U_n}{U_{nm}} \right)^2 . \qquad (3)$$

Terminal Velocity

The dispersed phase droplets formed in the storage media rise as a result of the density difference. The total area available for direct contact heat transfer is equal to the surface area per drop times the number of drops in the system. Holdup or volume concentration of the dispersed phase depends on the terminal velocity of the rising drops.

Swarms of moving drops have rise velocities that are different from those derived for single drops.[7] A free-surface cell model has been used to account for the hindering effects of neighboring drops on the velocity field. Holdup is an average statistical property characterizing an entire ensemble of uniform drops. The retardation effect of surface-active agents at the fluid-fluid interface has been analyzed. Numerous impurities in fluid-fluid dispersions can behave as surface-active agents. The terminal velocity of an ensemble of drops moving through a quiescent media in the presence or absence of surfactants has been given by Gal-or and Waslo[7]:

where a is the radius of the drops, γ is the surfactant retardation coefficient, and ϕ is the dispersed phase volumetric holdup. The equation is a generalization of Levich's solution for a single drop in the presence of surfactants ($\phi \to 0$), and of Happel's solution for an ensemble of solid particles [$(\mu^d + \gamma) \to \infty$)]. The hindering effect of volumetric dispersed phase holdup on the free area available for flow is illustrated by streamlines in Fig. 3.
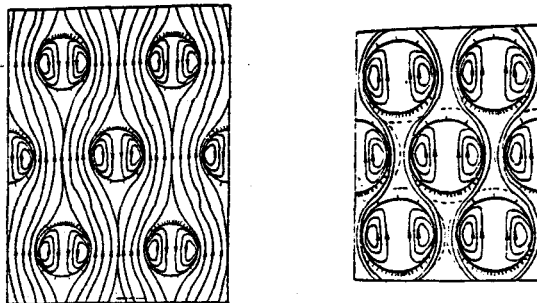

Fig. 3. Streamlines with a) 10% volumetric dispersed phase holdup, and b) 50% volumetric dispersed phase holdup.[7]

Continuous phase physical properties vary according to the extent of crystallization. These properties have a pronounced effect on relation (4), particularly with respect to viscosity. The viscosity of the crystallizing solution is approximated by an expression for concentrated suspensions[8]:

$$\frac{\mu}{\mu_0} = 1 + \frac{3}{(1/\phi) - (1/\phi_{max})} , \qquad (5)$$

where the solids fraction ϕ is the percentage of crystallization and ϕ_{max} is the maximum attainable solids fraction.

Internal Hydrodynamics

Prediction of the heat transfer coefficients between the drops and the continuous media is based upon suggested physical models of the heat transfer mechanism. In this paper, estimates are derived from three commonly postulated models: rigid drops, internally circulating drops, and completely mixed drops.[9] The heat transfer efficiency of a drop contacting a continuous phase is represented by the fractional approach to thermal equilibrium:

$$E_m = \frac{T_o - T_i}{T_c - T_i} , \qquad (6)$$

where T_i and T_o are the average inlet and outlet temperatures of the drop, and T_c is the constant temperature of the continuous medium. The general

$$U_{ens} = \frac{2(\rho_d - \rho_c)ga^2}{9\mu_c} \times \frac{3\mu_c(1 - \phi^{1/3}) + (1 - \phi^{5/3}) + (3 - \frac{9}{2}\phi^{1/3} + \frac{9}{2}\phi^{5/3} - 3\phi^2)(\mu_d + \gamma)}{2\mu_c(1 - \phi^{5/3}) + (3 + 2\phi^{5/3})(\mu_d + \gamma)} , \qquad (4)$$

3

expression for heat transfer between the two phases is[9]

$$E_m = 1 - \exp\left[-\left(A/V\rho C_p\right)_d U\theta\right] \quad , \qquad (7)$$

where A and V are the surface area and volume of the drop, respectively. The overall heat transfer coefficient U is defined as[9]

$$\frac{1}{U} = \frac{1}{h_c} + \frac{1}{h_d} \quad , \qquad (8)$$

where h_c and h_d are the continuous and dispersed phase transfer coefficients, respectively.

Drops behave as rigid spheres if surface tension forces prevent internal fluid movement. In such a case, heat transfer is limited by radial conduction within the drop, and the transfer efficiency in a rigid drop is given by[9]

$$E_m = \left[1 - \exp\left(- \pi^2 \alpha_d \theta / R^2\right)\right]^{1/2} \quad , \qquad (9)$$

where α_d is the dispersed phase thermal diffusivity, θ the contact time, and R the drop radius.

If surfactant impurities do not greatly retard or completely arrest internal circulation, a sufficiently large drop moving in a viscous fluid tends to circulate internally due to the shear stress applied by the continuous fluid at the interface. Compared to a rigid drop, internal circulation greatly enhances the rate of heat transfer. The circulation rate tends to increase with increasing drop size and viscosity ratio μ_c/μ_d. A model of drop circulation patterns using radial streamlines has been proposed by Handlos and Baron.[10] For this case, the internal Nusselt number is proportional to the Peclet number:

$$Nu_d = \frac{0.00375 \, Pe_d}{1 + \mu_d/\mu_c} \quad . \qquad (10)$$

External film resistance is neglected in the case of a circulating drop.

Wake translation behind a moving drop can strongly influence its flow behavior. The onset of wake shedding in drops has been reported at Reynolds numbers as low as 200.[11] Internal mixing is not expected until wake shedding occurs, although this does not constitute a sufficient condition for mixing. For the case of a completely mixed drop, the external resistance to heat transfer, $1/h_c$, is limiting, and the continuous phase Nusselt number can be expressed as[12]:

$$Nu_c = 5.52\left(\frac{\mu_c + \mu_d}{2\mu_c + 3\mu_d}\right)^{3.47}\left(\frac{D\sigma\rho}{\mu_c^2}\right)^{0.056}\left(Pe_c\right)^{0.8} \quad , \qquad (11)$$

where Pe_c is the continuous phase Peclet number, defined as DU_{ens}/α_c.

Direct Contact Model

Based on the controlling parameters, a computer model is used to predict the outlet temperature of the dispersed phase in a direct contact latent heat storage system. To isolate the dispersed phase temperature predictions, the continuous phase temperatures are taken to be the experimental values. The appropriate correlation to predict drop size depends on whether the drops are formed in the dropwise or jetting region. Although a distribution of drop sizes is expected in practice, heat transfer is based on the average drop size and no breakup or coalescence of the drops is included in the model.

The volumetric dispersed phase holdup in the storage media is predicted iteratively with the terminal rise velocity. In the terminal velocity equation, the retardation coefficient γ is assumed to be zero. The following equation is used to calculate holdup;

$$\phi = \frac{Q_{vd}\theta}{Q_{vd}\theta + V_c} \quad , \qquad (12)$$

where Q_{vd} is the dispersed phase volumetric flow rate and V_c the continuous phase volume. The residence time θ is calculated as

$$\theta = \frac{H}{U_{ens}} \quad , \qquad (13)$$

with the total height H of the two-phase mixture given by

$$H = \frac{Q_{vd}\theta + V_c}{A_c} \quad , \qquad (14)$$

where A_c is the cross-sectional area of the column.

Heat transfer between the storage media and the rising droplets is characterized by the fractional approach to thermal equilibrium. Given the inlet immiscible fluid temperature T_i and the continuous phase temperature T_c, the outlet temperature is calculated using an analytical expression for heat transfer. Such an approach is reasonable since the continuous phase properties do not change measurably during the rise time of a drop. The expression used to predict heat transfer is based on a rigid-, circulating-, or mixed-drop model.

For heat addition to storage, the heat transferred to the storage media, Q_{ex}, is equal to the sensible heat change in the dispersed fluid minus losses through the container:

$$Q_{ex} = \dot{m}C_p\left(T_i - T_o\right) - \left(\frac{T_c - T_a}{R_1}\right) \quad , \qquad (15)$$

where T_a is the ambient temperature and R_1 is the experimentally calculated resistance to heat loss in the container. The heat transferred to the storage media must equal the combined sensible and latent heat change in the continuous phase storage media. The sensible heat change in the storage material is known from the given continuous phase

temperature history. The change in latent heat content due to melting or crystallization yields a corresponding change in the solids fraction and, therefore, the continuous phase viscosity. It is assumed that the media is sufficiently well mixed, such that the suspension viscosity is uniform.

Comparison of the Model Predictions to Experimental Data

The predictions of the model are compared in this section with experimental data reported by Costello[13] for a similar system. Costello used Varsol 18, an immiscible organic fluid, to heat sodium phosphate dodecahydrate, which ideally melts at 34.1°C. System data was provided on temperature histories, flow rates, heat loss, and material properties. Values for certain properties of the constituent materials, such as interfacial tension, viscosity, and thermal conductivity, were not available; these were estimated from data for similar materials.[14,15,16]

Outlet temperature predictions based on a rigid-drop heat transfer mechanism are compared graphically to the actual data in Fig. 4. In the first 24 minutes of the melting curve, sensible heating
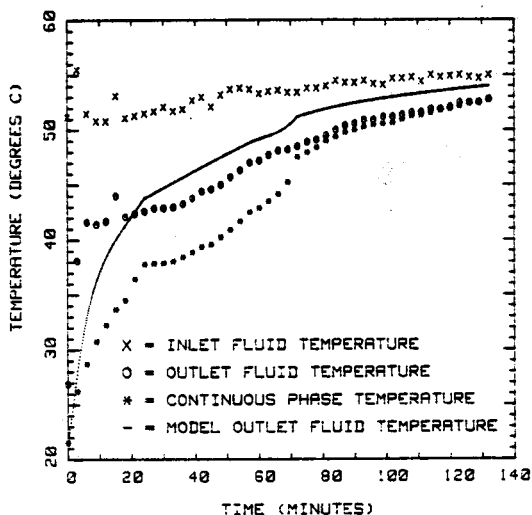

Fig. 4. Rigid-drop model prediction.

of the continuous phase salt slurry occurs; and the predicted outlet oil temperature is significantly less than indicated by the data. In the latent heat portion of the melting curve (>24 minutes), the experimental outlet temperature of the fluid is much closer to the continuous phase temperature than predicted by the rigid drop model. For the final heating portion of the curve, the agreement is also poor.

The rigid drop is a special case of a circulating drop in which interfacial tension gradients have arrested internal movement. This effect is opposed by the tendency for the drops to circulate in the viscous slurry. The lack of agreement between the data and the rigid drop model may be attributable to dominance of the viscous forces.

A graphical comparison of predictions and actual data is given in Fig. 5 for a circulating-drop mechanism. Again, in the sensible heat region, the model predicts better heat transfer than measured. Two possible effects should be considered for the initial portion of the heating curve. A high concentration of solids is present prior to melting. The resistance to flow due to drop-solid interaction is not necessarily accounted for in the viscosity expression. This effect would, however, tend to increase overall heat transfer effectiveness due to increased residence time. Channeling and phase segregation of the immiscible fluid through the salt is another possible occurrence. The presence of agglomerated solids could cause segregated, nondispersed flow patterns to develop, and decrease the residence time. Consequently, until the solids fraction dropped sufficiently to insure better mixing of the continuous phase, the heat transfer performance would be reduced from that predicted by a model that assumes a uniformly suspended slurry.
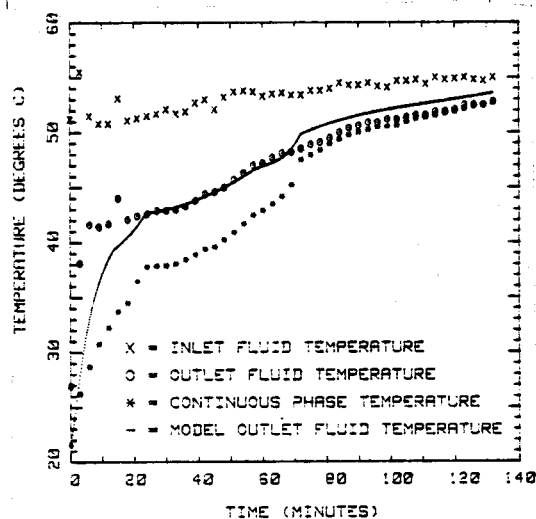

Fig. 5. Circulating-drop model prediction.

The prediction of the circulating-drop model corresponds well to the outlet temperature data in the latent heat portion of the melting history from 24 to 72 minutes, indicating that the model may be accurate. Comparisons beyond 72 minutes are suspect because the experimental outlet fluid temperature does not follow the inflection in the curve corresponding to the continuous phase temperature history, although the predicted value does. The accuracy of the data is limited by the small overall temperature differences in this region. Furthermore, different mechanisms may be controlling the heat transfer rate. The predicted Reynolds number is 36 near the inflection point of the melting curve at 72 minutes. For continuous phase Reynolds numbers higher than 20, the wake size can be large enough to significantly influence the heat transfer rate.[11] Although the predicted Reynolds number is somewhat uncertain, it indicates possible wake translation effects in this portion of the melt. Furthermore, the assumption of a quiescent continuous phase may not be valid in the melt re-

gion, since lower viscosity could result in continuous phase circulation, and significant backmixing and vortices may occur in the melted slurry.

Rapid internal mixing is caused by drop deformation, fluctuations, and oscillations. These effects are associated with large drop diameters and continuous phase Reynolds numbers of at least 200 to 500.[11] In such a case, the continuous phase heat transfer resistance is controlling. The external heat transfer coefficient was typically calculated to be about six times larger than the internal coefficient for a circulating drop; therefore, complete heat transfer is predicted if a well-mixed drop is assumed. Accordingly, the completely mixed model predicts an outlet fluid temperature equal to that of the continuous phase. The experimental values clearly do not support the well-mixed-spheres model, except in the end portion of the melting curve, where the accuracy of the reported data is questionable. Reynolds numbers of about 560 were calculated for the assumed case of a fully melted continuous phase, indicating that a well-mixed-spheres model could apply at low solids concentrations.

Conclusions

A model of direct contact heat transfer for latent heat storage has been developed based on existing information for drop formation, rise velocity, and heat transfer. Good agreement is achieved between the circulating-drop model and the available experimental data in the early melting region. As the slurry melts further, the circulating-drop model less successfully predicts the experimental results. Other intermediate mechanisms may exist between the circulating and well-mixed drop cases. Such behavior could be expected at the higher Reynolds numbers which occur when the melt viscosity drops. In the sensible heat portion of the melt cycle, none of the heat transfer models predicts the experimental data. The disagreement may be attributable to flow channeling effects, uncertainties in the drop size and viscosity correlations, weaknesses in the physical property data, or inaccuracies in the experimental data.

Although the initial limited agreement is encouraging, the available evidence is insufficient to conclusively validate the model. The existing model shows particular sensitivity to properties such as interfacial tension and viscosity. Further independent experiments are needed to test drop formation, holdup, heat transfer mechanisms, flow behavior, and physical properties. The calculated predictions can then be compared to a well-characterized experimental system, and the validity of this approach to quantifying direct contact latent heat storage performance can be tested.

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