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MASTER

DIRECT CONTACT HEAT TRANSFER
FOR THERMAL ENERGY STORAGE

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NOTICE

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Abstract

Direct contact heat exchange offers the potential for increased efficiency and lower heat transfer costs in a variety of thermal energy storage systems. SERI models of direct contact heat transfer based on literature information have identified dispersed phase drop size, the mechanism of heat transfer within the drop, and dispersed phase holdup as the parameters controlling direct contact system performance. However, current information is insufficient to predict these factors a priori. Therefore, tests have been defined and equipment constructed to provide independent determination of drop size, heat transfer mechanism, and hold up. In experiments with heptane dispersed in water, the equation of Kagen et. al. was found to most closely predict the drop size. The velocity at which drop formation changes from dropwise to jetting was overpredicted by all literature correlations. Further experiments are needed to conclusively determine whether the salt in a salt hydrate melt acts to block internal circulation. In addition, the potential of low temperature oil/salt hydrate latent heat storage systems is being evaluated in the laboratory.

Introduction

For both sensible and latent heat storage systems, heat exchange based on conventional equipment accounts for a substantial fraction of the total storage system cost. Direct contact heat transfer, the process of transferring heat across the interface of two immiscible phases without an intermediate heat transfer surface, offers both increased efficiency and decreased cost. However, direct contact heat transfer is not sufficiently understood to accurately assess its performance potential, therefore SERI's research is being directed toward predicting performance accurately enough to judge the potential of the technology.

Research at SERI is directed at understanding the basic mechanisms which govern direct contact heat transfer, assessing operational characteristics, and applying the knowledge to the development of more cost efficient thermal storage systems. During the past year, research at SERI has focused on testing mathematical models of direct contact heat transfer. Experimental work has focused on low temperature oil/water and oil/salt hydrate systems due to the relative ease of working at low temperatures, previous experience available in this temperature range, and the need to provide a definitive analysis of oil/salt hydrate systems.

Controlling Factors

Modeling efforts at SERI identified three parameters which control the rate of heat transfer in direct contact systems:

- droplet size,
- droplet internal heat transfer mechanism, and
- droplet residence time.

Each of these factors depends on the physical properties of the two phases and on designer specified characteristics such as distributor design and the superficial velocities of the two phases.

In FY80, experiments were initiated to independently determine these three parameters. A single drop column (Fig. 1) provides data on drop size as a function of fluid properties, injector nozzle diameter, and dispersed phase flow rate. The heat transfer mechanism between individual drops and the continuous phase is also determined with this apparatus. The multi-drop heat transfer column (Fig. 2) is used to study residence time, and to evaluate possible operating problems such as freeze up and carry over. In this paper, the results obtained to date on drop size and heat transfer mechanism are summarized.

Drop Size

Two regimes of drop formation are of interest in the design of direct contact heat exchangers: dropwise formation and jetting. At low flow rates, droplets grow while attached to the nozzle. When the upward force of buoyancy and the kinetic energy of the fluid leaving the nozzle exceed the retarding forces of interfacial tension and drag, the drop detaches and rises. This force balance is the basis of all the equations for predicting drop size in the dropwise regime (Scheele & Meister, deChazel & Ryan, Kagen et al.).[1]

When a drop begins to detach, a neck of fluid is formed between the nozzle and the drop. The neck elongates and thins, then breaks as the drop detaches. The forces of kinetic energy and excess internal pressure tend to hold the neck open, while interfacial tension attempts to thin the neck. As the velocity through the nozzle is increased, a point is reached where the stabilizing forces are greater than the interfacial tension. Above this velocity, drops are formed by the breakup of the jet. Equations predicting the transition point (Scheele & Meister, deChazel & Ryan, Ruff, and Lehrer) exhibit reasonable agreement among themselves, except at large nozzle diameters where only Lehrer's equation predicts finite jetting velocities.[1,2,3]

Below the jetting velocity, all drops produced are of equal size, during jetting a bi-modal distribution is produced. Two groups have advanced correlations for predicting the mean diameter of drops produced by jets, however, they are merely curve fits.[1]

Drop size is important for several reasons. As the drop becomes larger, its surface to volume ratio decreases; increasing the time required for a rigid drop to transfer a given fraction of its heat. A large-drop rises through the exchanger faster than a small drop, because buoyancy force increases as the third power and drag force as the second power of the diameter. However, the heat transfer rate may also increase with increasing radius due to enhanced internal droplet circulation and oscillation.

The single drop column is used to gather data on drop size and the onset of jetting. The basic apparatus is a

four-sided jacketed plexiglass column. Drops of the dispersed (oil) phase are injected through a glass nozzle at the bottom. Other interchangeable nozzles can be used so that the effect of nozzle diameter may be investigated. A heater controls the dispersed phase inlet temperature. Water can be circulated through the jacket to control the temperature of the continuous phase. The oil flow rate is measured with precision rotometers.

At low flow rates, the frequency of drop formation is measured with a stroboscope. Drop size is calculated from the frequency and measured flow rate. During jetting formation, the formation frequency is not constant and drop size is determined from photographs. The jetting velocity is defined as the velocity at which the droplet formation frequency ceases to be regular.

Comparisons of theoretical and measured drop size have been made with the water/heptane system. At low flow rates, the equation of Kagen et al. best describes the experimental data (Fig. 3). However, the velocity at which the transition to jetting occurs is overpredicted by all four available equations. In the jetting region itself, the existence of a bi-modal distribution is confirmed, but more data is necessary to determine the accuracy of the literature correlations. Additional experiments will be performed on oil/salt hydrate systems to determine whether the equations describe drop size for a surface active continuous phase where the continuous phase may be melting or freezing.

Drop Heat Transfer

For low conductivity materials such as oil, internal drop hydrodynamics determine the rate of heat transfer to and from individual drops. Small drops behave as rigid spheres, and internal conduction limits heat transfer. Larger drops may exhibit internal circulation, which will increase the heat transfer rate. Large drops may undergo oscillations which greatly enhance heat transfer. On the other hand, surface active agents may immobilize the interior of drops which would normally circulate.[4]

Heat transfer rates are correlated by an R factor, the ratio of the effective thermal diffusivity inside a drop to the molecular thermal diffusivity which would be exhibited for a non-circulating drop of equal size. The R value of a rigid sphere is 1, that of a circulating drop ranges from 1 to 5, while that for oscillating drops may range up to 100.

Experiments have been conducted with the single drop column to determine the effect of drop size and continuous phase composition on the internal heat transfer mechanism. Hot oil is injected into the column, and the flow rate is raised to a point just below jetting to achieve the highest flow rate possible while still producing equal size drops. Drop size is again determined from stroboscopic and flow measurements. The inlet and outlet temperatures of the dispersed phase and the continuous phase temperature are simultaneously recorded. The terminal velocity of the drops is measured and used to calculate the time required for a drop to move between the nozzle and outlet. The distance from column inlet to outlet is varied from 10 to 100 cm.

E_T is the amount of heat transferred by a drop divided by the maximum amount of heat which could have been transferred. If $\log (1-E_T)$ is plotted against residence time, the slope of the line yields R, and the intercept shows the magnitude of the end effects.

For the heptane/water system, the R value of 0.39 cm diameter drops was 1.4, while for 0.3 cm drops of Dowtherm J rising through molten sodium thiosulfate hexahydrate, the R value was not significantly greater than 1.0. In both cases, internal conduction limits the heat transfer rate. Further experiments will be necessary to determine whether the lack of circulation of the drop rising through the salt hydrate was due to surface active effects by the salt. Since the drop sizes were in the transition regime from rigid to circulating drops, the lower R value for the salt hydrate system may be due to the smaller drop diameter. Experiments will also be run to determine whether drops injected at temperatures below the freezing point of the continuous phase behave differently from hot drops due to the direction of heat transfer.

Conclusions

A column for determining drop size and heat transfer mechanism as a function of the relevant physical and operational parameters has been designed, constructed, and operated. During runs with the water/heptane system, the equation of Kagen et al. best predicted drop size. The nozzle velocity at which the drop formation mechanism changes from dropwise to jetting was overpredicted by all available correlations. The mode of drop formation in the jetting region has been observed, but sufficient data has not been analyzed to make a determination of the accuracy of the available literature correlations. The heat transfer rates observed were similar to those expected for a non-circulating drop, but the drop size was small enough that surface tension may have retarded circulation. Further information is needed to determine whether drop circulation is inhibited by the surface active action of salt in a salt hydrate melt.

Future Plans

Experiments will be continue with the single drop column to determine whether the equations for predicting the transition to jetting and dropsize during low flow and jetting are applicable to salt hydrate phase change systems. Additional experiments will determine droplet internal circulation effects on the salt system heat transfer.

The multi-drop column has been constructed, and is operational. This apparatus will be used to test models of holdup and to provide an experimental assessment of direct contact heat exchange applied to low temperature salt hydrate storage systems. The problems of freeze up and carry over of the continuous phase into the oil loop will be investigated.

References

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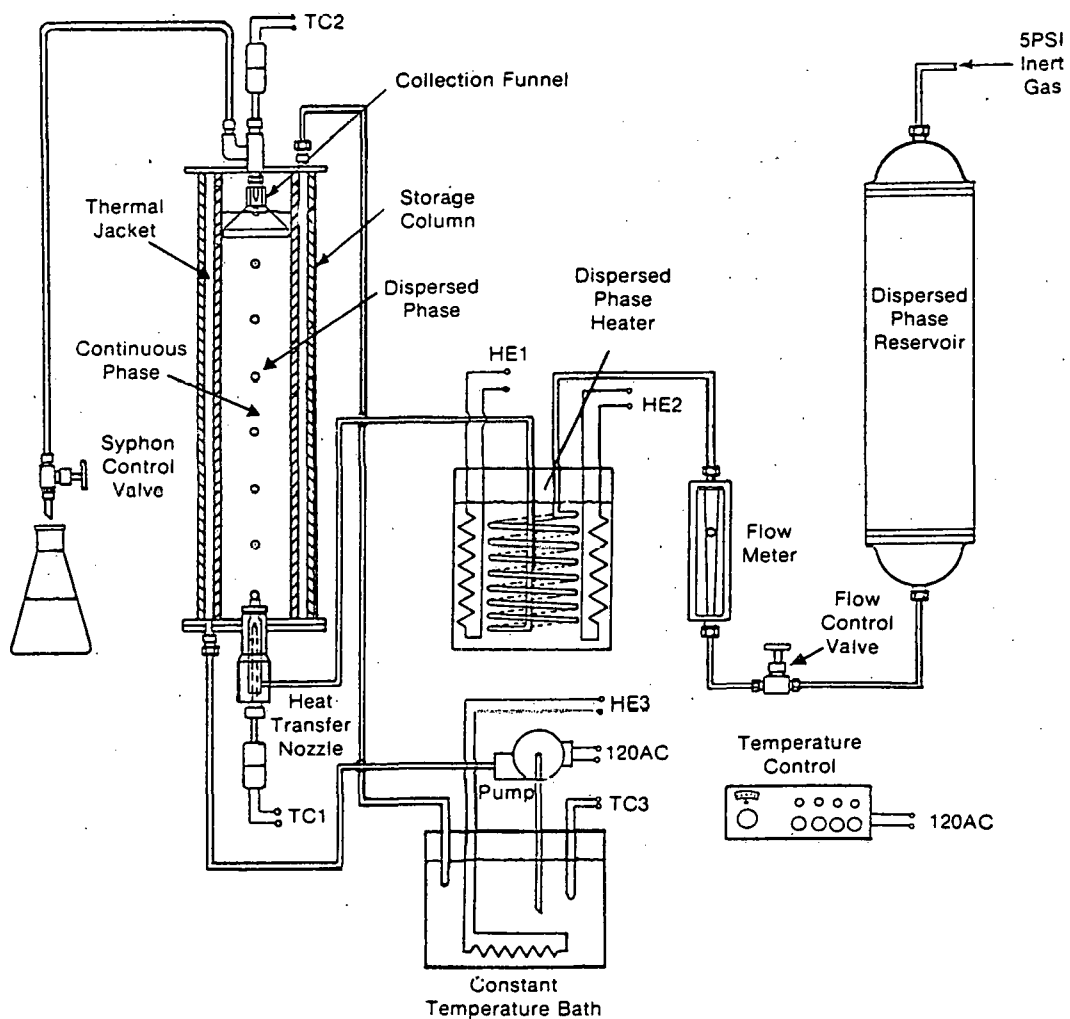
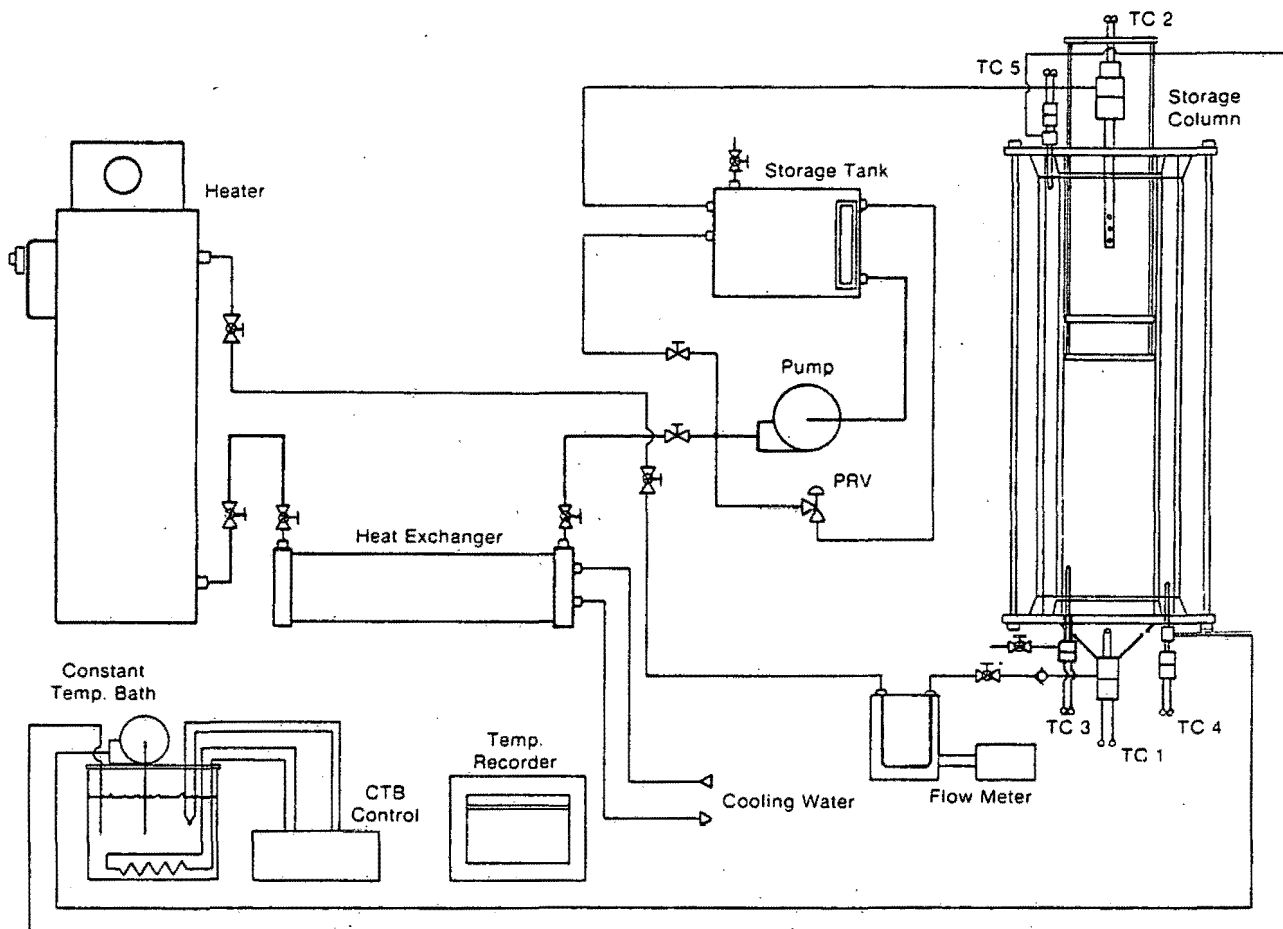Figure 1. Single Drop Heat Transfer Column

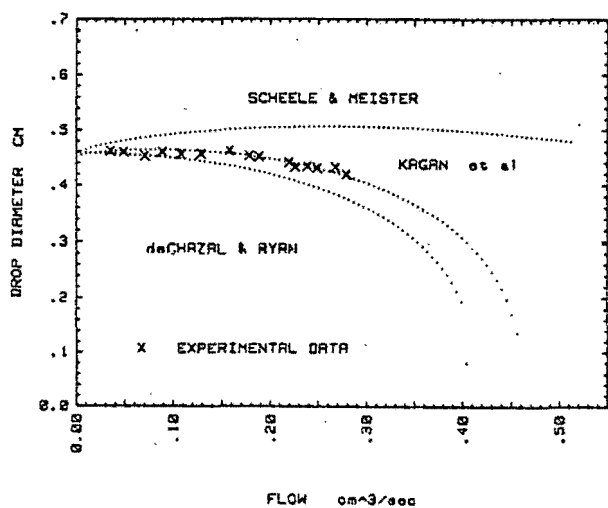Figure 2. Multi-Drop Heat Transfer Column

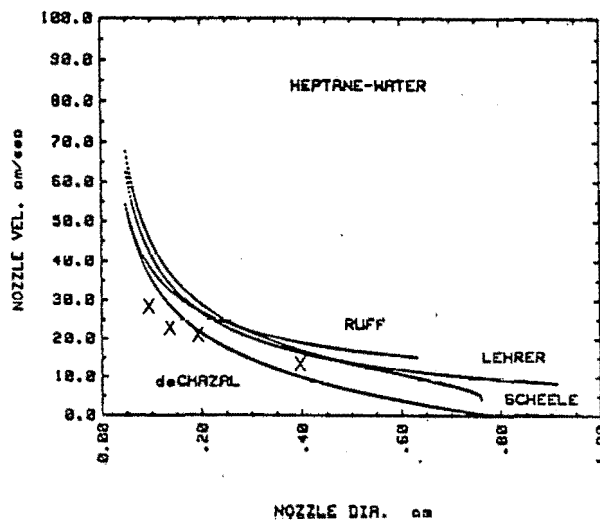Figure 3. Drop Diameter vs. Flow Rate for the System Heptane/Water, Nozzle Diameter = 0.13 cm

Figure 4. Jetting Velocity vs. Nozzle Diameter for the System Heptane/Water