ACTIVE HEAT EXCHANGE SYSTEM DEVELOPMENT FOR LATENT HEAT THERMAL ENERGY STORAGE

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PROJECT OUTLINE

Project Title: Active Heat Exchanger System Development for Latent Heat Thermal Energy Storage

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Project Goals: Develop an active heat exchange system, utilizing a phase change thermal storage medium, where operating characteristics are compatible with a 250° to 350°C steam power cycle.

Identify and select concepts for test.

Design, fabricate, assemble and test laboratory scale modules.

Evaluate results.

Recommend further development requirements.

Project Status: Heat exchanger tubes coated with 1-2 mil electroless nickel were tested in a 600°F molten/hydroxide environment. Latent heat extraction could not be satisfactorily demonstrated in this experiment due to low heat transfer coefficients (90-250 BTU/hr-ft^{2}-°F for salt-oil T's between 5-50°F).

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ACTIVE HEAT EXCHANGE SYSTEM DEVELOPMENT FOR LATENT HEAT THERMAL ENERGY STORAGE

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SUMMARY

Alternative mechanizations of active heat exchange concepts were analyzed for use with heat of fusion Phase Change Materials (PCM's) in the temperature range of 250° to 350°C for solar and conventional power plant applications. Over 24 heat exchange concepts were reviewed, and eight were selected for detailed assessment. Two candidates were chosen for small-scale experimentation: a coated tube and shell heat exchanger and a direct contact reflux boiler.

A dilute eutectic mixture of sodium nitrate and sodium hydroxide was selected as the PCM from over fifty inorganic salt mixtures investigated. Based on a salt screening process, eight major component salts were selected for further evaluation. Using an economic assessment program coupling the candidate salt mixtures and heat exchange concepts, $NaNO_3$, $NaNO_2$, and NaOH appeared to be the best major components in the temperature range of 250 to 350°C. The minor components, selected in similar fashion, are NaOH, NaOH, and $NaNO_3$, respectively.

Preliminary experiments with various tube coatings indicated that a nickel or chrome plating or Teflon or Ryton coating had promise of being successful. An electroless nickel plating was selected for further testing. A series of tests with nickel-plated heat transfer tubes showed that the solidifying sodium nitrate adhered to the tubes and the experiment failed to meet the required discharge heat transfer rate of 10 kW(t).

Testing of the reflux boiler is under way. Direct injection of cool high-pressure water as a spray into the ullage was accomplished and steam was generated. The injected water was compatible with the salt mixture under the conditions imposed. An improved injector and a modified water preheater are being readied for "full up" testing.

INTRODUCTION

Thermal energy storage (TES) is important for efficient use of energy resources. Advanced storage technologies can improve the operation and economics of electric power systems by storing excess off-peak energy for later use in meeting peak demands.

In electric utilities, baseload is the round-the-clock load that is met with the most fuel-efficient equipment. As the daily load increases, the utility incrementally brings the next most efficient equipment on-line. For the near term, energy storage can effectively increase the use of existing baseload equipment. In the longer term, energy storage can increase the percentage of baseload capacity. Thus, there is an economic incentive for utilities to use baseload plants to meet the peaking loads now met by less fuel-efficient equipment.

Energy storage is a practical necessity for solar-thermal generation of electric power. It is necessary for plant stability and control issues related to high-frequency solar transients. Two techniques can be used to maintain the reliability of the grid with a large solar plant on the line. In the first technique, the solar plant is backed up with a conventional plant that is pressed into service as needed after available instantaneous solar power has been supplied to the grid. The second technique controls the delivery of power to the grid so that the collected energy can be stored when it is available and not needed to meet grid demand. This stored energy becomes available for electric generation when the demand is high and direct insolation is not available.

For these applications, the specific operating conditions and machinery typically used in power plants needs to be considered. The operational regime of conventional turbomachinery is shown in Figure 1. In Figure 2 operating conditions for current and advanced solar power plants and for utility systems are shown with corresponding entry flow temperatures. Notice that most of the steam power plants operate within a band of 4.1 MPa to 16.5 MPa (600 psia to 2400 psia); the saturation temperatures corresponding to these pressures are between 250° and 350°C.

Heat from storage is used to boil water and provide high-temperature steam to the plant. To provide steam at 250° to 350°C, heat should be stored at a temperature greater than the desired steam temperature. With an assumed temperature drop of 18°C, the useful temperature range for storage media is from 268° to 368°C. Salts with melting points up to 400°C were thus considered in PCM selection.

SELECTION OF HEAT EXCHANGE CONCEPTS

A candidate heat exchange concept applicable to latent heat thermal storage units must be capable of transferring heat from a source into the frozen medium causing it to melt. Likewise, the concept must be capable of transferring the thermal energy stored in the medium to a sink while the medium undergoes a solidification process. In both cases, the concept should permit relatively high heat transfer rates while undergoing the phase changes.

Because of Honeywell's experience using inorganic salts with active heat exchange devices, a dilute eutectic medium was used as a basis in formulating candidate concepts. Experience in working with dilute eutectic media indicates that the charging or melting process is not a critical issue; heat transfer during solidification from the melt is the major issue.

A survey of heat transfer and chemical processing literature was made to determine the equipment used industrially and the chemical and physical processes exploited in extracting the latent heat of fusion from a melt. An investigation of crystallization process was performed to determine if existing industrial methods might be directly applicable to or provide new ideas for latent heat storage design.

The processing literature is limited in coverage of heat exchanger crystallizers, as this approach has often been disregarded in favor of alternatives. The major design and operating problem of a cooling crystallizer is crystal deposits on the heat exchanger tubes. Once this takes place, the accumulation can increase rapidly, and not only does the heat transfer from the molten salt decrease dramatically, but the solids are not in a mobile form for pumping. Following is a list of different methods used in the past and innovative ideas put forth by Honeywell engineers to overcome the solid film problem.

- Mechanical Solids-removing Techniques:
    - Agitation
    - Vibration
    - Ultrasonics
    - Internal surface scrapers
    - External surface scrapers
    - Flexing surfaces
    - Tumbling solids
    - Fluidized beds
- Hydraulic Techniques:
    - Flow variations
    - Fluid pulsing
    - Jet impingement
    - Sprayed surface exchanger
    - Freeze-remelt
- Techniques Involving Physical Properties of the Salt:
    - Crystal volume change
    - Crystal weakening additive
    - Conductivity-enhancing additives
    - Magnetic susceptibility
    - Electrostatic separation
    - Finishing and coating of heat-exchanger surfaces
    - Delayed nucleation and supercooling
- Other Concepts:
    - Direct contact heat exchange
    - Shot tower latent heat of fusion concept
    - Prilling tower crystallization
    - Liquid metals salt system
    - Immiscible salts

  - Encapsulation (passive system)
  - Distributed tube exchanger (passive system)

From the survey, Honeywell selected the following concepts as candidates for further evaluation.

- Internal Surface Scraper
- External Surface Scraper
- Coated Tube and Shell
- Jet Impringement
- Reflux Boiler/Self-pressurizing
- Reflux Boiler/Continuous Salt Flow
- Reflux Boiler/Continuous Salt Flow with Hydraulic Head Recovery

  Direct Contact Heat Transfer
- Tumbling Abrasive

These concepts embody the most conventional and promising heat transfer processes. The passive tube-intensive system was chosen as a reference system against which cost comparisons could be made.

A comparative analysis of the active heat exchange systems listed indicates that the most economical systems are those that employ the most compact heat transfer surfaces. The compactness of the tube and shell heat exchanger and the high heat transfer rate associated with the direct contact reflux boiler concept are the two features that appear to be the most promising for large-scale implementation, i.e., 1000 MW(t) rate and 6-hour capacity.

The coated tube and shell concept capitalizes on commercial availability of tube and shell heat exchangers and assumes successful development of a non-stick finish for the exchanger tubes. Studies and discussions with consultants have indicated that there is a good possibility of achieving major reductions in the adhesion strength of solid salts to the cold metal surfaces of the tubes. One technique suggested is polishing the heat transfer surfaces to minimize the mechanical bonding of the salt to the surface. Another technique involves the application of a thin coating of an amorphous material or a material with a crystallizing structure different from, yet compatible with, the salt. This might reduce bonding strength of the microscopic scale.

The second system recommended for further study is the direct contact reflux boiler. Although two heat exchange processes are used (salt to water/steam and condensing steam on tubes), the individual thermal resistances are so low that their sum is less than the thermal resistance of most liquid-to-pipe-to-pipe-to-liquid exchange processes. Consequently, a high overall heat transfer coefficient can be continuously maintained. Furthermore, the system can be designed to operate without salt transfer pumps. This is accomplished by gravity filling the refluxing boiler and subsequently expelling the slurry with residual steam pressure.

Improved thermal efficiency through elimination of the heat exchangers can be achieved in a system where the heat transfer medium is the working fluid. The lifetime of this type of system is directly related to the content of salt remaining in the working fluid as it enters the turbine. The salt content can be minimized by good separator design.

COATED TUBE AND SHELL HEAT EXCHANGE CONCEPT MECHANIZATION

The coated tube and shell heat exchange system for use with molten salts is similar to any conventional tube and shell heat exchange system. The differences lie in the tube surface property and the heat storage medium. Available evidence indicates that the proper choice of tube surfaces, surface preparation, and medium selection will reduce the salt-to-tube bond strength to permit the solid salt to be removed by modest hydrodynamic forces.

Analysis showed that the tube and shell heat exchange system was the most cost-effective closed heat transfer system. Only the open-cycle reflux boiler, which can take advantage of a higher output temperature, shows possibilities of being more cost-effective. From the hardware development standpoint, the tube and shell heat exchanger technology is better developed and more widely used than any other industrial heat exchanger technology. The main questions to be resolved in its application to molten salt thermal storage are the suitable combinations of surfaces and medium, and the temperature, flow rate, and heat rate range within which the system can be operated.

Figure 3 is a diagram of a typical counterflow heat exchanger with an enlarged section of tube broken out to illustrate the different surface conditions to be explored. Figure 4 is a schematic diagram of a 1000 MW(t) system with 6 hours of storage capacity using tube and shell heat exchangers to effect the removal of the heat of fusion from the molten salt medium thermal storage. For this system, it is expected that the maximum slurry density that is readily transportable in the pipe lines will be on the order of 20 percent. To achieve high latent heat recovery from storage, the slurry is returned to storage where gravity separation is used, causing the solids to settle to the bottom of the tank. The less dense liquid rises to the top to be recirculated through the exchanger.

In a large heat exchanger, as was considered for the large-scale system, the fluids in the course of a single pass through the exchanger will flow past several hundred rows of tubes as dictated by the tube sheets (baffles). It becomes a monumental task to build a small heat exchanger model with hundreds of ranks of tubes, but the effect can be approximated by recirculating the flow repeatedly over the same tubes. This was the approach decided upon for this experimental model.

COATED TUBE AND SHELL EXPERIMENT

This experiment, shown schematically in Figure 5, consists of an insulated mild steel tank that is heated externally with controllable guard heaters. A sump-type pump is mounted in the main storage tank such that the pump is always immersed in molten salt. A discharge line connects the salt pump to the flowby module. The module consists of a rectangular chamber with a tubular cross-flow heat exchanger which extends across the test chamber.

The solid tubes are inactive; i.e., they do not transfer heat but are flow patterns. Fifteen tubes, 19 millimeters in diameter, are arranged to transmit heat (plain tubes). These tubes are blanked off at the outboard ends and fed with cooling oil from a manifold through concentric internal tubes. Heated oil flows out through the outlet oil manifold.

The tube bundle is arranged with separator plates and, together with the oil manifolding, may be removed as a unit for servicing and changing of coated tube elements. When the unit is inserted into the test chamber, salt flow, as shown by the arrows in Figure 5, passes through the tube bundle three times. Turning vanes maintain a proper flow pattern to simulate a large tube bundle.

A discharge duct located above and at the outlet of the tube bundle and the salt stream channels the flow back to the tank. A butterfly valve regulates the back pressure and flow level in the channel. A force guage attached to a contoured pintle measures changes in momentum of the salt slurry. By measuring the liquid height and by knowing the force, the salt slurry flow can be calculated. An electrical contact probe was planned to determine liquid levels in the flow meter. A small quantity of salt will be continually drained off the channel through a tube. This salt will flow into the main settling tank.

REFLUX BOILER CONCEPT MECHANIZATION

The reflux boiler concept of heat exchange is depicted in Figure 6. The molten salt thermal storage medium is pumped at high pressure into the pressure vessel, where water is injected into the salt. The water flashes to steam, which raises the pressure. The steam flows to a shell and tube condenser. Here the steam condenses and transfers its latent heat to boil the water flowing inside boiler tubes. This steam can be delivered to a turbine. The condensate is collected and refluxed into the boiler to start the cycle over. Because the condenser and reflux boiler both operate at nearly the same pressure, the condensate pump need only supply enough head to overcome the salt hydrostatic head and the throttling necessary to achieve balanced flows through the injection nozzles.

The salt slurry leaving the reflux boiler has a larger potential energy due to the high pressure. A hydraulic expander can be used to recover the VdP energy by directly coupling the expander to the pump. For incompressible fluids, a well designed pump can be run in reverse to recover head. Therefore, the expander can be a well designed motoring pump. Salt level control in the reflux boiler will be maintained by modulating the slurry discharge stream.

A commercial size thermal storage system is shown schematically in Figure 7. This system was sized to deliver 1000 MW(t) for 6 hours using eight refluxing boilers and eight condenser units. Molten salt is pumped from the top of the storage tank through the reflux boilers, and the salt slurry is directed back into the bottom of the storage tanks. Settling, with increased separation of the liquid and solid phases, will occur in the storage tanks to increase the percentage of latent heat recoverable.

REFLUX BOILER EXPERIMENT

The experimental apparatus used to model the reflux boiler system for a 10-kWh(t) capacity and 10-kW(t) rate must resolve the technical issues yet circumvent the development of expensive, specialized equipment. This can be done by operating the model in a batch mode and using compressed gas to transfer the molten salt into the system. This eliminates the need for a high-pressure salt pump. In addition, the low-head, high-temperature pump necessary for feedwater refluxing is replaced by a low-temperature, high-pressure pump and water preheater.

The experimental apparatus, shown in Figure 8, consists of a reflux boiler nearly filled with molten salt into which hot water is injected under high pressure. The molten salt gives up heat to boil the water. The steam bubbles to the surface of the salt and passes to the condenser, where it condenses on the cool condenser coils heating the secondary heat transfer fluid. For the experiment, the secondary fluid will be heat transfer oil Mobiltherm 603 to provide close temperature control and high heat transfer rates without using a high-pressure recirculating water loop.

The water-steam cycle will not be operated in a refluxing mode, but will be operated open-loop to provide an accurate means of measuring and controlling the water injection rate. This is achieved by measuring the rate of water uptake at the pump suction port. The condensate receiver provides a means of collecting and storing a nominal 15-minute flow of water, which can later be cooled and analyzed for salt content to estimate salt carryover. Further analysis of salt carryover can be made by disassembly of the shell and tube condenser at the end of a test run.

The advantages of this mechanization from a modeling standpoint are:

- No high-pressure pumping of salt is required.
- No throttling of a high-pressure salt or salt plus water is required.
- No valves in the salt lines must be opened or closed while high-pressure differentials exist across them.

EXPERIMENTAL RESULTS

Coated Tube and Shell Flowby

Testing of the coated tube and shell flowby concept has been completed. The module was exercised over a range of ΔT's and salt flow velocities for a given maximum oil flow rate. The tube bundle was plated with 1 to 2 mils of electroless nickel in accordance with MIL-C-26074B. The heat exchange module failed to meet the required 10 kW(t) heat extraction rate. Overall heat transfer coefficients ranged between 500 to 1500 $W/m^2-{}^oK$ for salt velocities of 0.5 to 1.5 m/s and temperature differences of 2^o to $12C^o$. For a given salt velocity and ΔT, the heat transfer coefficient decreased with time, indicating the buildup of a salt layer on the tubes. Increasing the salt velocity improved the heat extraction rate, but increasing the ΔT for a given salt flow did not improve the heat extraction rate.

Reflux Boiler

Testing of the reflux boiler is under way. Direct injection of cool, high-pressure water as a spray into the ullage was accomplished, and steam was generated. The injected water was compatible with the salt mixture under the conditions imposed. An improved water injector and modified water preheater are being readied for "full up" testing.