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DESIGN OF COLD STORAGE DEVICE FOR A LOW TEMPERATURE THERMAL ENERGY TRANSMISSION SYSTEM EMPLOYING HYDROPHILIC MATERIALS

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ABSTRACT

In this work undertaken to design and develop a number of cold storage devices is described. All the units employed hydrophilic particles hydrated with water as the phase change element. This work has yielded a cold storage device suitable for demand side management applications. The first part of this work discusses previous work carried out employing hydrophilic materials for cold storage, before this work began. Next the problem of fluidising hydrophilic particles using minimal power is readdressed, the design of a new system discussed, and its performance and limitations identified. Then the modifications made to this system to increase the energy density, are reported.

The process of fluidising the whole mass of stored solids limited the performance of the developed systems. Based on the acquired knowledge a fresh approach overcoming this problem was identified. Finally, the design, construction, and operation of this system are discussed and recommendations made.

KEYWORDS: Slurry, Heat Transfer Rate, Thermocouples, Thyrister

INTRUDCTION

Literature

The potential for using fluidised beds consisting of hydrophilic particles for thermal energy storage had previously been the theme of two MSc projects. The first of these [1] investigated using both air and oil to fluidise the hydrophilic particles. The main focus of the air fluidisation tests were for hydrophilic particles of diameter 0.4mm in a small bed (155mm dia, height 280mm). Calculations of the minimum fluidisation velocity were made using Eqn1.1. It was found that for fully-hydrated particles fluidisation did not occur at the calculated minimum velocity, and as the air flow rate was increased further severe channelling occurred. The main reason cited for failure was the tendency of the particles to adhere and form large dense agglomerations. The addition of a dry powder did not appear to improve the situation. However it was possible to achieve fluidisation if hydration levels were kept below 16% by weight to fluidise larger particles of 1.25mm diameter were not successful due to the absence of an air supply capable of providing a sufficient flow rate across the particle bed.

The failure of air fluidisation led to attempt fluidisation using both silicon oil and mineral oil as support fluids. The advantage of using a liquid can be seen by inspection of Eqn.1.2, where the small density differential and the increased viscosity combine to reduce considerably the minimal fluidisation velocity. The test apparatus consisted of a tank open top cylinder of 195mm diameter and 230mm height. Cooling of the mixture was achieved via a cooling coil positioned in the oil particle mixture in the tank. The fluid was stirred using a small turbine blade on a driven shaft. The tests proved

successful for both oils and for particle concentrations from 10% to 40% by weight. The test took the mixture through the phase transition temperature down to -4°C. All materials were fully hydrated 75% hydrophilic particles.

This work was continued the following year by [2] where a focus was made on the use of oil as a support fluid. A new test apparatus, similar to [1] was designed and constructed. The major improvements were replacing the cooling coil with a cylindrical heat exchanger, construction of a close fitting turbine, and general improvements in tolerances around the device. Shown in Figure 1 the heat exchanger consisted of a number of turns of copper tubing enclosed between two copper cylinders, and to make good thermal contact the volume was filled with a low melting point alloy called Woods Metal. The final dimensions were OD = 124mm, ID = 96mm and height = 156mm. It was attached to the top of the tank by three studs.

The main body of the device was a cylinder (190mm ID), constructed from tank so that flow visualisation could be made. The use of tank also benefited the design due to its relatively high thermal resistance. To further reduce the heat gains, the unit was placed inside a box constructed of polyurethane board with a removable side for inspection and visualisation. Cooling was supplied via anti-freeze solution cooled by a chiller unit.

A number of tests were performed using this apparatus; the varied parameters were the support fluid, the solids concentration, the vertical position of the turbine, and its speed of rotation. With a 25% solids concentration in mineral oil the system was found to agglomerate and block at obstructions encountered at the top of the tank. The turbine was run at a rotational speed of ~600rpm, although it was found that varying the speed up to ~1000rpm for short intervals improved The best results were achieved with the turbine blade at the base of the heat exchanger. Similar results were obtained with a 40% solids concentration in silicone oil. The effect of varying the speed of rotation was more beneficial in this instance, although agglomerations still occurred. Below a mixture temperature of -2°C it was noted a stable mixture could be achieved using a constant rotational speed, furthermore this could be reduced down to -300rpm. In all the tests passing below the phase transition temperature, no increase in the heat transfer rate was recorded.

PRELIMINARY TESTS

Discussions in this work have described the high torque requirements encountered while agitating high concentration slurries, a situation not acceptable in the context of a system aimed at demand side power reductions. The configuration chosen for this work was to use a pumped system to mobilise the hydrophilic mixture over the heat exchanger surface end, a suitable pump had to be chosen and some idea of the limitations of the pump had to be found in terms of the concentration of solids that it could pump, and the rates at which the slurry could be pumped.

For simplicity and low cost, an impeller type pump was considered the most suitable unit although it had to meet certain requirements. The first of these was a geometry and construction that would not cause degradation of the particles in the slurry. This required spacing greater that the particle size (1-2mm) and elastic surfaces on the impeller that would not damage the particles on impact. Secondly it must operate in the required temperature range (30°C to -10°C) and any elastic properties of the impeller surface should not be lost at low temperatures. Finally, it must have a low power rating (<100W) both in respect of the power demand required to operate it and the amount of heat it dissipated, and possibly leaked, into the system. Many manufacturer products were investigated but most were classed as unsuitable for fluids containing particles, and hence rejected. Furthermore the power rating and operational temperatures of the pumps were unsuitable.

The only impeller pumps found that were suitable for the geometric requirements of this system were domestic/industrial washing machine pumps. These had both semi flexible impellers, and wide spacing between the impeller and body (~5mm) (designed to cope with hard particles such as coins and buttons). They also had low nominal power ratings of 50 to 100W. It was not known if these pumps would operate at the lower temperature ranges required for this project, so after visual inspection one was bought and tested. The construction enabled easy disassembly and the semi-flexible impeller blades were removed and cooled down to -27°C. At these temperatures they were still found to be reasonably flexible. The pump body was made of a thermo-setting plastic. The inlet port was constricting although there was enough wall material to allow it to be machined to larger diameter (24mm). The outer diameters were suitable for attachment to 28mm copper piping using a short length of PVC hose.

Two simple tests were performed on the pump, the first was to measure the maximum achievable flow rate, and the second to check the highest concentration of solids that could be pumped. The first test used a large tank of water from which the pump inlet was connected. The outlet was returned to the tank via 3m of PVC tubing (28mm ID). The flow was diverted to a bucket for a known time interval and the collected mass measured. The receptacle used to collect the sample was floated in the main tank during the period; this negated the change in head and the flow rate achieved was 28lt/min. The second test used a simple closed loop of copper tubing (28mm ID) with a small heat exchanger in line. The loop was filled with a measured volume of silicone oil. Solids were added and the volumetric concentration calculated by measuring the spill from a small outlet. The resulting mixture was pumped while being cooled down to -5°C. The slurry was found to be pumpable in the system at concentrations of 50% at room temperature, but blockage occurred during the phase transition temperature (0°C). The previous concentration of 40% had continued to circulate through the phase transition temperature down to -5°C. Both tests suggested that the pump was suitable for the investigations to be undertaken during this work.

COLD STORAGE DEVICE

The failure of air fluidisation had led to the use of oil for the supporting mixture. Such systems had been shown to work although not at a scale large enough, or a state stable enough, for practical purposes. This part of the work describes the development of a cold storage unit addressing both of these problems. As a design guide the system aimed at meeting a latent heat storage capacity which would facilitate a discharge of l kWh (3600kJ), at a rate of 1kW.

TANK TEST UNIT

A test unit to allow the development of a cold storage device capable of agitating high solids concentration slurry was designed and constructed. The main body consisted of a flanged cylinder with four small ports, and a top and base constructed from aluminium (Plate1). The ports were tapped to accept standard 28mm pipe fittings for the connection of circulation loops. The base had a central recess to support a vertical shaft that formed the basis of agitation devices. This shaft passed out through a hole in the top plate. Perspex was used at this stage to allow the visualisation of flow and effectiveness of mixing within the unit as modifications were made. The tank had an internal diameter of 294mm and height of 430mm and without the connection of circulating loops gave a maximum volume of ~301t. No means of cooling was added at this stage because an effective method of mobilising the slurry with low energy input was being investigated and the thermal behaviour of hydrophilic particles at the phase transition temperature were being examined.

This diameter gave an area of 4.8×10^{-2} m^2, hence from the use of two pumped loops a maximum mean velocity of ~2×10^{-2} m/s was expected across the area of the tank. The support fluid used to fill the tank was Shell. At room temperature a hydrophilic particle of 2mm diameter had a settling velocity of ~1×10^{-3} m/s (Eqn 2.2). This velocity will be reduced even further in practice by hindered settling, due to the presence of other particles. Hence the pumps had the capacity to fluidise the material within the system. The initial test used a solids concentration of 30%.

The shaft was driven by a shunt motor rated at 190 Watts and fitted with an internal gearbox giving a maximum of 200rpm at the motor output. This was further reduced to 120rpm through the use of a toothed belt and pulleys between the motor and shaft by a thyristor controller.

Initial tests looked at the behaviour of just pumping the slurry in the device. Firstly it was found that during static periods settling of particles soon occurred. Because of this pumps had to be located in such a position that particles settling under gravity fell away from them. Secondly, severe channelling occurred in the bulk of the mixture as shown in Figure 2.

The next solution replaced the paddles with a semi-circular disc with its axis orientated to the shaft and positioned vertically, so that it was just above the lower inlet port of the tank. This orientation of the disc swept a very small area through the settled solids, while rotated, and gave very little resistance during start up conditions. The combination of the rotating distributor and pump reduced channelling considerably splitting the contents of the tank into two regimes. One consisted of recently settled material the other was an evenly dispersed mixture of solids and oil.

The least mobilised zones were close to the outer surface of the tank (Figure 3) due to the tendency of the flow to emerge from under the disc to take the shortest path, this being near to the centre of the plate. To improve this further the disc was changed from a semi-circle to a three-quarter circle. The behaviour was similar although the outer regions were now disturbed as the gap in the plate swept past. Also it was noted that at 30rpm the whole contents were mobilised. The torque required at these rates of rotation was still excessive, so it was decided to add three more three-quarter discs to the distributor. These were evenly spaced vertically and the gaps were offset at 90° to each other.

The level of fluidisation was significantly improved (Figure 3) with this option although on each plate a volume of hydrophilic material was seen to settle. This was on the opposite quarter to that of the plate opening. This phenomenon was found to be independent of the direction of rotation of the shaft. The method of construction of the shaft and plates did not allow the plates to be modified to remove the quarter where settling occurred, furthermore the gap between the tank wall and the plates' edges was large allowing flow to bypass them. Hence at this stage it was decided to design and build a working device for evaluation.

COLD STORAGE DEVICE MK I

This design was of similar dimensions to the tank test unit, although some consideration had to be given for both the of a heat transfer surface and thermal insulation. The main body of the tank was fabricated from aluminium, because of its combined resistance to corrosion and good heat transfer qualities. A coil of 8mm copper refrigeration tubing was placed around the outer cylindrical surface and enclosed in another aluminium cylinder.

To achieve a high degree of thermal insulation a casing was built to surround the main body of the tank, allowing for the circulation pumps to be located externally. The base of the tank was supported by 55mm thick expanded

polystyrene sheet, whilst the annular cavity of 80mm wide was filled with loose polystyrene beads. The rate of heat gain to the systems was calculated at 1.9 W/°K. This was later found to be out by nearly a factor of 2, and estimated from performance measurements to be 3.6(±0.8)W/°K

The distributor shaft and plates (Figure 5) were constructed from SS. Each plate had opposed quarters removed; also the shaft was hollow allowing thermocouples to be placed on the surfaces of the plates (Figure 5) to measure the temperature of the mixture. To accommodate the rotation of the shaft the thermocouples had to be connected to a silver slip ring device. To achieve this, small areas of the outer casing were removed (10mm × 10mm) and the Wood's metal removed to expose the inner cylinder.

Initial performance tests were conducted on the system before the phase change materials were added. The purpose of these was to determine the heat gains to the system from the pumps, the distribution device and the local environment. The tank was initially filled with a 30% by mass ethylene glycol solution (32.51t). The whole system was cooled using a chiller down to a specific temperature. Once this had been reached the unit was allowed to operate continuously for 24 hours while temperatures around the system were measured. From these tests, it was estimated that the pumps were injecting heat at an average rate of 7.4(±0.8)W each, whiles the agitator was dissipating heat at a rate of 10.2(±0.8)W 1rps. The mean heat transfer coefficient for this system, with both pumps operating, was estimated at h=400(±100)W/m^2/°K. The inner heat transfer surface had an area of 0.15m^2, and for a load at 8°C this would give heat transfer at a rate of 360W to 600W at the operational temperature of 0°C. This unit was operated below the phase transition temperature, although all tests to date had been at room temperature (~18°C). To compensate for this it was decided to use an alternative support fluid that had viscous properties similar to those of the [3] at low temperatures.

The hydrophilic particles were prepared by hydrating, rinsing and draining before placing then in polythene bags. Each bag contained 1kg of hydrated material; these were thermally cycled between 18°C and -27°C by employing a domestic freezer.

The first test employed only one pump with the agitation device set to 15rpm. The initial temperature was 22°C and it was observed that only a few very small particles were being brought to the surface. This showed that little fluidisation was taking place. The test was allowed to continue to see if the increase in viscosity caused by reduced temperature would initiate full fluidisation. This did not occur even at -5°C. The chiller unit was switched to heating mode and the system brought back up to 22°C. The following test repeated the conditions of the first, except that the agitation rate was set at 60rpm. This gave a definite increase in the rate at which particles were rising. This increased as the temperature of the system decreased, although even at -5C° only small quantities of the material were being drawn into the circulation loop.

In the next test the rotation rate was set back to 15rpm but both pumps were operated. The effect of the second pump was dramatic. From observations full fluidisation appeared to be taking place throughout the temperature range of 20°C to -4°C. As the temperature dropped below 0°C small agglomerations were seen to be rising from the distributor. These were random in shape but had a characteristic size of 10mm. The structures were easily broken up with the tip of a temperature probe. Part of the insulation was removed form one of the circulation loops allowing the flow through the PVC connection on the outlet of the pump viewed. This revealed that no agglomerations were surviving passage through the pump.

Once the cold storage unit was back to ambient temperature, the tank inspection cover was removed and the aluminium top fitted. The system was insulated and the outer casing closed for a full analysis. The test followed the same procedure as the previous one. Data from the thermocouples indicated that the mixture was virtually isothermal and mixing was thorough. Furthermore the temperature measurements on the discs showed no deviation compared to the mean indicating that settling was not occurring as had been seen on the three-quarter plates of the tank rig. After a period of two and a half hours cooling the chiller was switched to heating mode, while data collection continued, until five hours into the test.

The mean temperature behaviour is shown in Figure 6; a number of points should be noted. Firstly there is a clear difference in the rate of cooling and heating above 0°C, these results from the chiller performance. Secondly, on the heating portion of the curve there is a double plateau which was unexpected. The first, starting at about 3.5h into the test (~0.4°) is believed to result from phase change in the particles. The shorter one at 0°C was believed to result from free water within the mixture. This water has possibly two origins. The first source may be free water remaining on the particles after preparation. The second explanation may be that the water originated from inside the particles, as their temperature decreases a slight reduction in maximum hydration level occurs resulting in free water. The heat transfer coefficients were estimated to be 800(±100)W/m^2/°K at 4°C dropping with temperature down to 400 W/m^2/°K at -3°C. The decrease was associated with a viscosity increase as the fluid cooled, although the higher value relative to that of the glycol charge could be due to particle effects. After disassembling the top of the cold storage rig the charge was increased to 20% and the tank top put in place. The relative success of the tests with a 10% hydrophilic charge was not repeated with a concentration of 20%. Cooling occurred well, down to below 0°C, although the agglomerations were clearly larger than with the 10% tests. Again the temperature probe could be used to break up their structures, and none were visibly surviving the pumps. As the temperature reached -2°C the agitator was noted to be juddering, and occasionally the drive belt slipped. This increased in frequency, until finally, it jammed solid, at the same time flow in one of the circulation loops stopped.

Cooling at this point was stopped and the chiller switched to heating mode. After 10 minutes the distributor could be rotated but with high resistance. Also the pump left in operation was not successfully fluidising the particles; the behaviour was similar to that in the initial test with 10%. As the temperature of the fluid reached 0°C it was noted that large particles were rising to the surface. These were much larger than those observed previously, their size close to the diameter of the outlet tube to the pump. Initially these agglomerations were drawn into the pump, although blockage of the remaining loop soon followed due to several lumps locking together and obstructing flow. After the second loop finally became blocked the distributor came to a halt, probably due to the settled particles. The system was allowed to warm over night to ambient temperature.

Analysis of this situation suggested that water was causing the particles to bond together in the low flow conditions found at the surface of the wall. The particles that rose to the surface were assumed to be formed under more turbulent, or less cold, conditions, hence their weaker structure. Attempts were made to reduce the free water in the system by the addition of some dry hydrophilic particles and operating the system at ambient temperatures for 24 hours. However, a subsequent cooling test failed in the same manner as before. It was apparent that the mixture had to be kept in a highly turbulent state during freezing conditions to inhibit, or at least reduce the production of agglomerations. This was a major problem and required a new design of the distributor.

TANK RIG MODIFICATIONS

The failure of the previous rig at 20% solids concentration was considered to be due to ice bonds forming between particles close to the cold surface of the tank wall. The test indicated that under highly turbulent conditions such particles were not formed. The options available were (a) add more pumps in order to increasing the flow rate and hence the degree of turbulence, or (b) cause the flow to be limited a reduced cross section of the tank for short period, again increasing the turbulence of that zone but for a limited duration. The first option was rejected since it would increase the electrical demand of the system which would impair its effectiveness as a demand-side management device. Therefore it was decided to form zones within the tank by placing a number of vertical baffles in the tank with a single rotating disc at the base, to regulate the flow into the zones (Figure 7).

For test purposes a set of six baffles, equally spaced, were placed vertically in the tank, and a disc with a single sector cut into it was fitted onto the drive shaft (Plate1). The single pump loop was replaced with two new loops containing heat exchangers. The new system was constructed and tested using the 20% mixture from the last set of tests with Fusus oils as the support fluid. Initial tests under ambient conditions were encouraging. The system was seen to force the slurry out of each of the zones as the distributor rotated. The same occurred during cooling and the system was found to be stable, no blockages occurred at a temperature of -2°C after prolonged operation (5 hours). During heating, large lumps were seen to rise to the surface as seen during the heating of the previous rig. These were large initially and fell back into their zones as the distributor moved round.. This was designed out in the new baffle system for the cold storage tank.

COLD STORAGE DEVICE MK II

A new baffle system was designed and fabricated for the cold storage tank the vertical blades were supported by the use of a cylindrical tube which attached to the top plate of the tank. The relatively large diameter was used to avoid constricting geometries in the system, and only caused a reduction in volume of ~3%. The method of fitting the blades to the support tube allowed four, six or eight blades to be attached at even spacing. The distributor disc had an open sector of 70°, this could be varied by a closing plate down to 30°. An external heat exchanger was also designed for the tank that cooled both flow loops, but kept them separate.

Thermocouples were placed at the top, middle and base of two opposing plates. Pairs of thermocouples were also placed at both the glycol inlet and outlet ports to the heat exchanger. Also still in use were the four thermocouples on the body wall. The system was filled with water for calibration, the volume was found to have increased to 34.751t as a result of the addition of the modified pump loops and the external heat exchanger. The tank insulation was changed, instead of the loose fill of polystyrene beads, 19mm sheet Armaflex was used, with a secondary layer of 50mm foil backed fibreglass sheet. Two semi-circles of 26mm thick cellular polyurethane board were used for a removable covering at the top of the tank. The insulation type was changed on account of the new heat exchanger and to simplify assembly.

The tank was drained of its charge, dried, and filled with 24.3 lts of Fusus oil in preparation for the addition of 30% by volume of hydrophilic particles. Before the 30% charge was re-introduced to the tank, the shaft position was adjusted to reduce the gap between the distributor disc and the base of the plates. This was done to ensure that flow only passed into one zone at a time as the distributor. Flow was found to be stable, although below 0°C a build up of material was observed to occur at corners of the plates Figure 8. The shape and size of the build up was independent of the zone in which it occurred. Cooling was allowed to continue down to -3°C and then the system was shut down.

The tank was allowed to warm back to ambient temperature and the cooling test was performed again, down to a temperature of -5°C. Figure 9 shows the mean temperature of the fluid mixture in the system. The phase change commenced at just below 0°C but it is unclear as to what point it finished. The calculated change in the energy content of the mixture. The energy-temperature curve (Figure 10) showed that this was not occurring at 0°C. The gradient of the curve was much higher below the transition temperature.

Once the system was below -5°C, the chiller was switched to heating mode and the data logging software started again. The flow behaviour of the system was similar to that cooling phase below -0°C. Once phase transition started large agglomerations started to rise to the surface of the tank and when drawn into the pump inlets, temporary blockage soon resulted. These agglomerations were removed manually with a temperature probe, and flow continued for a while until larger lumps rise. These were pushed above the fluid surface, the effect of which was to reduce the level of the fluid at the pump ports to a point where air was entrained. This resulted in complete failure of both pumps virtually simultaneously and the test was repeated several times under different conditions.

FEED BASED SYSTEM

The limited success of the fluidising cold storage units caused a reassessment of the method used to mobilise the store. The fact that the pumps used operated well for solid concentrations up to 30% significant. This suggests that higher densities were required in the main store then a method of feeding the agitation/heat-transfer system, at suitable concentrations, had to be found. To achieve this settling nature of the particles in the fluid was exploited using a method that fed settled particles into a turbulent steam of clear fluid. This passed the resulting mixture through a heat exchanger and returned it to the top of the tank (Figure 11). The fluid and particles were separated at this point, the particles falling on top of the remaining settled mass while the clear fluid was pumped around the system again.

This design had a number of advantages over a fully fluidising device. Firstly, the rate at which the feed device was operated would control the solids concentration passing into the heat exchanger. This could effectively regulate the rate at which the store was charged. It also meant that the feed rate could be varied as the store was cooled or heated to maintain a maximum rate of heat transfer for the existing slurry properties. Secondly, at zero feed rate the circulation system would be cleared of particles making maintenance much simpler. Thirdly, the behaviour of the transmitted slurry would be independent of the geometry of the storage part, hence the system would be relatively easy to scale up. Fourthly, the potential for pumping only in the loop containing the clear fluid would enable the use of well developed high efficiency single phase pumps. Finally, the circulation loops could be feasibly extended to any extent, allowing the slurry to be distributed over a range of distances.

A system was designed similar to that shown in Figure 12; although for test purpose a second pump was added onto the slurry-side of the circulation loop. The design of the feed mechanism was based upon construction considerations, which suggested a final arrangement where the outer diameter for the feed device was 80mm. The drive shaft diameter was 25mm and the pitch for the feed helix was 20mm. Hence the maximum volume displaced for each rotation of the device was ~0.91t. Using an estimated flow rate of ~0.51t/s from the pumps, a concentration of 30% would require a volumetric feed rate of 0.251t/s of the settled mixture; hence the drive shaft had to rotate at ~15rpm.

The main part of the tubular tank had a diameter of 300mm, and a height of 970mm. The volume available for settled particle storage, including the feed section, was estimated to be 461t. This allowed for a vertical separation between

the surface of the settled particles and the clear fluid outlet of 170mm. Also the design gave a depth of 100mm of fluid above the outlet port, to avoid air being entrained as occurred in previous systems. The intention was to restrict all heat transfer to occur in the external circulation loops. These consisted of 28mm copper tubing, with fittings added for the placement of thermocouple probes to measure the mid-stream fluid temperature. The heat transfer sections were of a concentric tube type, with an active length of 1.58m, giving a total heat transfer surface of ~0.14 m^2. At an estimated flow rate 0.51t/s, a mean fluid temp of 0°C, and mean wall to fluid temperature differential of 5°C, values of h~500W/m^2/K were estimated (Eqn 2.39). This would give heat transfer rates of 350W at 0°C compared to estimated heat gains of ~50W. This was sufficient to cool the systems enough to check the principles of operation. This would be more severe with this system due to the increased mass, and the reduced area of the base. Furthermore it would not be very stable. The design incorporated three brackets on the main body of the tank that would accept / inch diameter rods. The use of adjusting nuts on the rod ends allowed the tank to be maintained level. The rods avoided thermal bridging between the tank and the ground Plate 3.

The device was partially assembled to test the feed rate of solids into the mixing chamber. A mass of fully hydrated hydrophilic particles was placed in the main tank, and the motor used to turn the feed helix a few times. The material falling from the system was collected, the mass recorded, and then replaced at the top of the tank. Rates of discharge were much lower than expected at 33(±2) grams per revolution, in terms of volume this was an order of magnitude lower. The tests proceeded, as it was believed that; (a) the support oil would assist the movement of particles through the feed device, and (b) the pumps could be controlled to create a pressure differential between the main chamber and the mixing chamber to enhance the feed rate.

Once the system had been fully assembled, the re-hydrated particles were added followed by the support fluid. A new method of removing the excess water from the particles employing a centrifuge was used. The chiller unit was connected to the heat exchangers, and for initial test purposes the system was wrapped in foil backed fibre glass blankets. The system was run initially at ambient temperature with both pumps full on and the feed device set at a rotational speed of 60rpm. Inspection of the flow at both the top of the tank and clear connections at the pumps, suggested that the system was working as required. It was noted however, that a small fraction of the particles were not settling out between the inlet and outlet ports at the top of the tank, and were being drawn back around the system. The system was stopped and some tubular inserts were added to divert the flow and create conditions similar to those found in a cyclone (Figure 12).

When the tank was next started it was found that the inserts were very effective at separating the support fluid from the particles, although after several minutes of operation the particle concentration of the return flow was very low. The rotation rate of the distributor was increased to 120rpm, but little benefit was observed. This suggested that the discharge rate from the feed device was actually lower than that measured with out the support fluid. The ac voltage to the pump on the clear fluid side was decreased, using a variable transformer, to try and induce a pressure differential between the mixing chamber and the main chamber. The motor of the pump was a shaded pole type, this did not respond well to variation in voltage and control was not possible.

Instead the pump was simply turned off. This resulted in a drastic change in the conditions. A large burst of particles were seen to be returned to the top of the tank, although this decreased to a lower, stable state after a few minutes. The pump in the clear fluid loop was seen to be turning, which indicated that the slurry was still flowing. The system was set to cool and a thermocouple, attached to the end of a im long rod of PTFE, was used to measure the temperature at

various depths and radii of the main tank. As the tank cooled it became clear that it was not behaving as expected. Temperature measurements indicated that the main flow of the fluid-particle mixture had formed a channel though the centre of the system (Figure 13). The majority of the particles appeared to have settled and formed a conical shape in the main body of the tank. This was confirmed after draining the system.

MODIFICATIONS TO MK III

Modifications were made to the rig to overcome the aforementioned problems. The first of these was to replace the small diameter feed helix with one of diameter 298mm located just above the lower ridge in the main tank (Figure 14, Plate 3). This had a pitch of 20mm and had turns. The lower inlet port of the tank was re-located to be just below the new feed plate. Its entrance was changed from being normal to the circumference of the tank, to entering at a tangent, so that the fluid rotation impinging on the lower plate would result in downward deflection. Similarly, the return flow to the top of the tank was at a tangent to the circumference of the tank body. This was to produce the cyclone effect that proved effective in the initial tests Finally two throttling valves were added to both the inlet and outlet ports at the base of the tank, to enable the inducement of a pressure differential between the volume of settled solids and the mixing flow.

On return of the modified parts the tank was partially reassembled and tests were made to determine the feed rate for the particles as previously described. The results were encouraging, giving a feed rate of 3.1(±0.2)kg per revolution. This suggested a rotational rate of -3rpm would be required to achieve a 30% solids concentration in the flow. This was below the minimal rate achievable with the motor and pulleys, although tests with the previous rig suggested that discharge rates would be lower once the support fluid was added. After full assembly of the modified system the previously used charge (mixture) was returned to the tank. Care was taken doing this so as not to cause solids to be flushed into the narrow mixing chamber.

The start up of the tank was performed by engaging both pumps, but with the distributor drive stationary. This was to ensure that no solids were discharged into the flow causing blockage. Both of the throttling valves were fully open. Under these conditions it was observed that a general rise in settled mass was occurring, indicating that the pressure in the mixing chamber was too high.

The same start up procedure was followed the next day although the valves were left in their original positions. After an initial burst of particles, solids were no longer seen in the flow around the loops. The source of these particles was either from material that had fallen from the feed plate overnight, or due to an imbalance in the differential pressure across the feed plate while the pumps started. Activation of the feed device produced a controllable feed rate of solids to the system as noted previously. The device was shut down and an insulating cover was applied. The chiller unit was connected and the system started again.

The feed rate was set at a low setting (~15rpm) and the device cooled. To check the temperature of the system at different depths and diameters, a probe was used.

As the system reached 0°C particles failed to completely separate at the top of the tank. The quantities involved were small and gave no problems at this stage. It was assumed that these were fine particles (< 1 mm diameter), their smaller size not allowing them to settle at a high enough rate to separate from the fluid. The oil level was also noted to have dropped slightly, although not enough to cause air to be entrained into the inlet port. When the temperature of the fluid had reached -3°C the settling rate appeared lower and more particles were drawn into the outlet port at the top of the

tank. The motor to the feed unit was stopped. The concentration of particles returned to the top of the tank reduced but did not stop. The cause of this was seen to be the stirring of the settled mass, which appeared to have risen to a higher level than the start of the test. This was considered to be due to a general decrease in the settling rate of the particles because of an increase in viscosity of the oil, increased density of the oil, and a reduction in the density of the particles due to freezing, or the formation of lose agglomerations. The pumps were shut down and the system allowed to settle for an hour.

The temperature probe was used to determine the temperature distribution throughout the system before it was restarted. The measurements showed that the bulk of settled particles were at 0°C, the outer regions were above this due to the flow of heat from the outer surface. All material was found to have settled and the height of the surface decreased. Only the pumps were started at first, and after an initial flow of particles decreasing over a few minutes, none were seen to be entrained. The top surface of the settled particles was agitated by the flow, although not to a degree that caused particles to be drawn into the outlet. The agitator was switched on and particles were again fed into the system. These separated well at the top of the tank. The chiller unit was switched back on in heating mode and the system allowed to heat. The temperature of the return flow was taken up to 8°C, by which time all probe measurements indicated that the solids in the system were above 4°C. The system was shut down.

To overcome the problem of excess agitation at the top of the settled particles several iterations were performed to reduce the flow rate of the fluid. To achieve this the throttling valve on the outlet of the mixing chamber was closed slightly. After this operation the other throttling valve was adjusted to balance the pressure differential as described above. After a degree of adjustment the distributor system was switched back on and found to be stable. The chiller unit was used to cool the contents again. During this cooling test the problem of the surface material being excessively agitated was significantly reduced, and although not fully cured, did not cause a failure of the system. The test was continued until the particle bulk contained in the system had dropped below -2°C. The system was again stopped and allowed to relax for an hour. Start up of the unit was successful and again no problems were encountered during the discharge phase. The test has been repeated since and no problems have been encountered.

DISCUSSIONS

The work reported in this was undertaken to investigate methods of mobilising phase change particles forming the active medium of a thermal energy store device. The initial approach was to fluidise the entire contents of a storage unit with a suitable supporting fluid. This found a degree of success although the achievable concentration of solids was limited. This in turn prohibits the maximum energy densities of such a system, making them unsuitable for thermal energy storage applications.

The second approach adopted was to continually feed a high density particle bed into a turbulent stream. This provided slurry with a controlled solids concentration. This slurry could be pumped to external heat exchangers allowing the contents of the system to be cooled. The solids were returned to the high density particle bed after passing through a cyclone, this allowed the clear fluid to be passed on and reused at the feed device. This system proved stable at all of the temperatures tested.

The system can be considered of consisting of three components, (i) The main storage vessel, (ii) The distribution unit (feeder) and, (iii) The separator (cyclone) unit. The maximum energy density of the entire system is limited only by

the packing density of the solids within the storage vessel, this is a function of the particle size distribution used. Another advantage of this system over the first approach is that the phase change slurry can be pumped to the point of application.

All heat transfer to the storage medium is external to this device which enables the choice of heat exchanger units to be made to achieve the desired performance of the system. For thermal engineering applications it is recommended that further investigations are made regarding the distribution unit and the separator, to increase performance and produce design data.

Equations

$$V_o = \frac{g\left(\rho_g - \rho_f\right)d^2}{18\mu} \tag{1.1}$$

$$V_o = 0.2\left[\frac{g\left(\rho_g - \rho_f\right)}{\rho_f}\right]^{0.72} \frac{d^{1.18}}{\left(\mu/\rho\right)^{0.45}} \tag{1.2}$$

$$V_o = 1.74\left[\frac{g\left(\rho_g - \rho_f\right)}{\rho_f}\right]^{0.5} d^{0.5} \tag{2.2}$$

$$Nu_D = \frac{\left(f/8\right)\left(\mathrm{Re}_D - 10000\right)\mathrm{Pr}}{1 + 12.7\left(f/8\right)^{1/2}\left(\mathrm{Pr}^{2/3} - 1\right)} \tag{2.1}$$

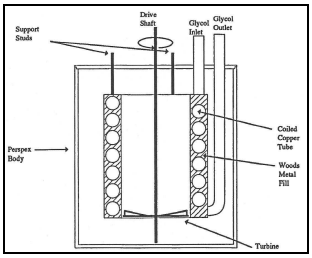

Figure 1: Cross Section of Cold Storage Unit

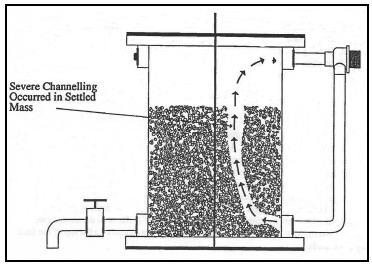

Figure 2: Channelling in Perspex Test Unit

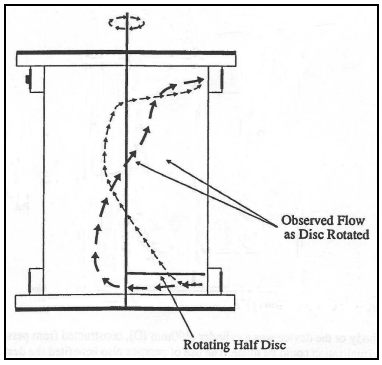

Figure 3: Flow Pattern for Single Plate

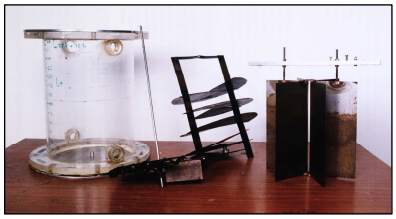

PLATE 1

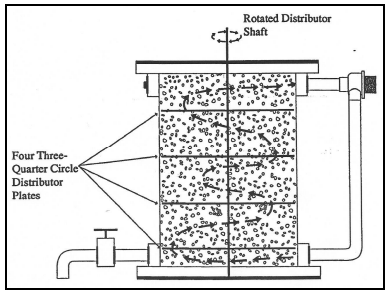

Figure 4: Four Three-Quarter Circle Plates

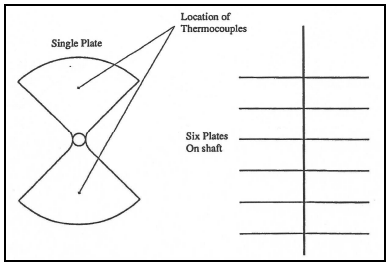

Figure 5: Schematic Placement of Thermocouples

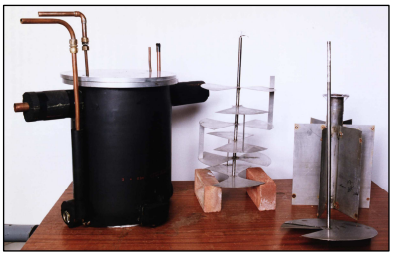

PLATE 2

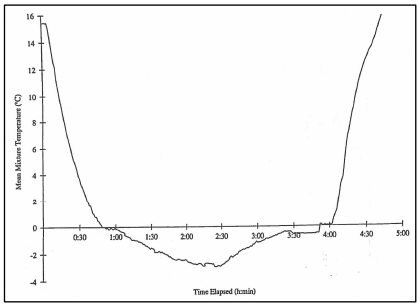

Figure 6: Modified Baffle System for the Cold Storage Tank

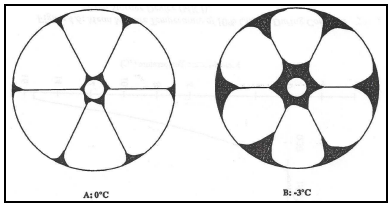

Figure 7: Increase in Agglomerations of Baff led Zones Tempature

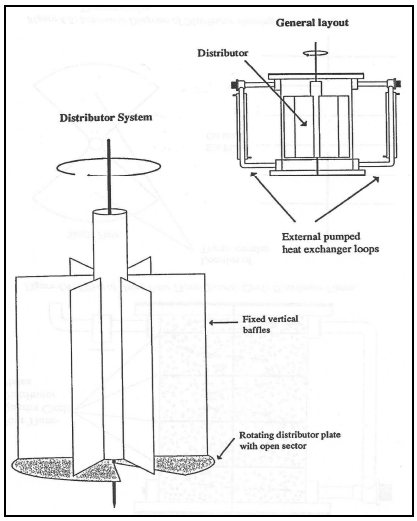

Figure 8: Details of the Modified Baffle System for the Cold Storage Tank

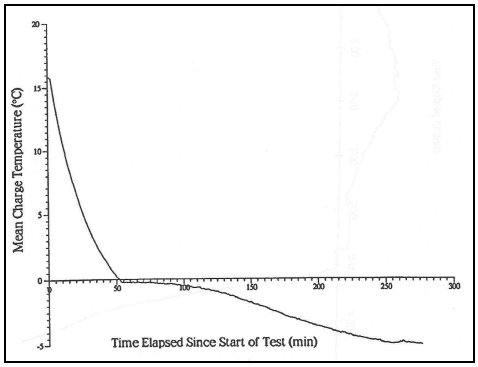

Figure 9: Mean Temperature of 30% Charge in the Cold Storage Device (MK II) During Cooling Period

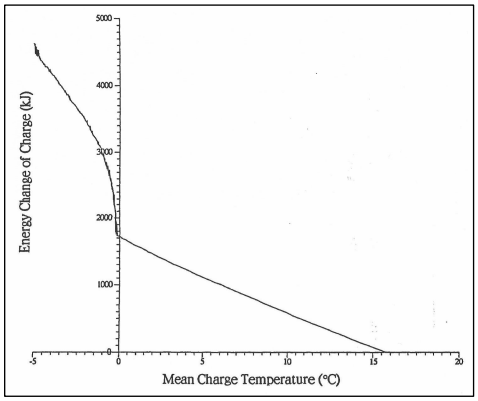

Figure 10: Energy Change of 30% Charge in the Cold Storage Device (MK 11) During Cooling Period

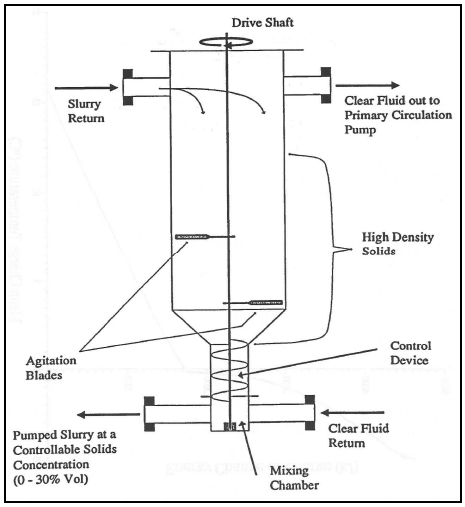

Figure 11: Layout of Feeder Based Cold Storage Device

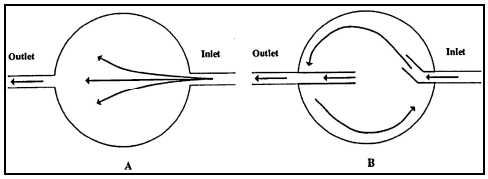

Figure 12: The Flow Pattern (A) Initially, (B) After the addition of Inserts

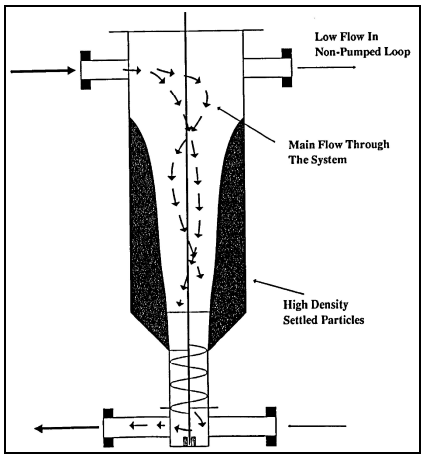

Figure 13: Channelling Occurring in Cold Storage Device

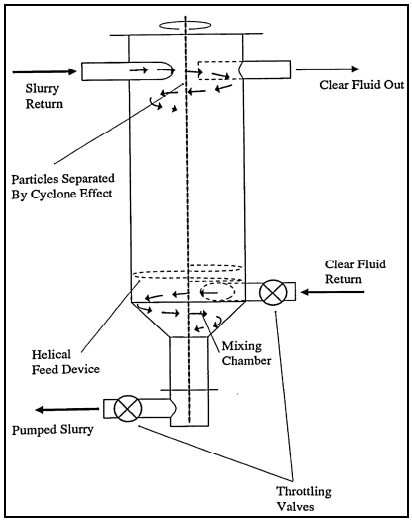

Figure 14: Schematic Diagram of the Final Design of the Feed-Based Cold Storage Device

PLATE 3

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