The heat produced by solar energy or by nuclear energy is stored with Hitec (eutectic NaNO₃, NaNO₂, KNO₃). For the recovery of the heat the molten salt is injected into an organic oil. The influence of temperatures and velocities of molten salt and oil on the average diameter of particles is studied. All the experimental results can be correlated with a single dimensionless number giving the efficiency of the apparatus.

1. INTRODUCTION

In order to use new forms of energy it is necessary to store it. Indeed some sources as nuclear energy yield a continuous output, some others, as solar energy, are essentially intermittent, and finally energy consumption essentially fluctuates. In order to lower costs and to save energy, one has to put in reserve the energy during low consumption periods or over production to carry it over for times when conditions are reversed.

Different ways of storage can be considered. At the present time the thermal energy storage with molten salts is probably one of the most interesting processes. These generally exhibit a good temperature stability, they have high heat capacities and latent heat, they do not require equipment under pressure (as is the case for water).

Two kinds of thermal storage can be considered:
- storage by sensible heat
Some industrial achievements already exist: for instance the experimental solar plant called "Themis" (1) and solar houses at Le Havre (2) in France. But this process presents some drawbacks. To store a large amount of energy one has two possibilities, either to increase the temperature and so, new technological problems occur (like the...
corrosion, the efficiency of solar captors at high temperature, etc...) or to increase the volume of storing fluid which has other problems (volume of apparatus, price...). Finally the apparatus does not work at the constant temperature level generally imposed by a thermodynamic chain.

- storage by latent heat of fusion 
  In this case the stored heat is important: for instance with NaCl, the heat stored by latent heat is the same as is stored by sensible heat over 418°. In this case the use of the change of state avoids using a wide range of temperatures.

With the eutectic mixture (7% NaNO₃ - 40% NaN₂O₂ - 53% KNO₃) named Hitec the latent heat corresponds to an interval of 54° and its use allows lower temperature operation for solar collectors. In both cases technological problems are simplified. In conclusion the storage by latent heat exhibits undeniable advantages but heat recovery is difficult. Two kinds of recovery can be considered.
  - Static recovery, which can be described as a heat exchanger tube in a vessel. The molten salt can be either in the vessel or in the tube. But in both cases the salt crystallizes on the exchange wall, and this hampers the thermal transfer on account of the bad thermal conductivity of the solid crust (3-4); the efficiency is bad.
  - Dynamic recovery. In order to increase to a maximum value the exchange surface between the molten salt and the heat transfer fluid, the former is sprayed into the latter. The two liquids can go in the same way or countercurrent. But the chief difficulty is to find two fluids which are totally inert chemically and not soluble at all within each other. These conditions can be achieved with only a few systems:
    - metal-molten salt (5-6)
    - gas-molten salt (7)
    - organic oil-molten salt (4)
In this work, we present a study of experimental results obtained with an exchanger using the couple Hitec-gilotherm (organic oil).

2. DYNAMICAL EXCHANGER

   It is described in detail in another paper (8). The apparatus is described in Fig.1. Initially the salt (solid) is in the storage tank, 1, then it is heated to the liquid state close to the melting temperature by Joule effect; at the same time the oil is heated in the tank, 2, to the temperature chosen. The circuits between different tanks are pre-heated in order to avoid obstruction and thermal loss - all the tanks and circuits are thermally insulated.

   Then the molten salt is injected into the flow of organic oil in the exchange column, 3, where the heat of salt (mainly the latent heat) is transferred to the oil. The resulting mixture is liquid-liquid at the top and solid-liquid at the bottom. It is received in the tank, 4, where a sample of crystallites is taken off for a gra-
nulometric study. Then the salt is melted, the mixture is driven toward the tank, 1. There the oil is pumped into, 2. In order to determine the thermal balance we measure:
- molten salt temperature $T_i$
- oil temperature $T_h$
- mixture temperature $T_m$ (at the bottom of 3)
- oil flow $\psi_h$
- molten salt flow $\psi_i$

In all experiments the diameter of injection and $T_i$ were kept constant.

3. AVERAGE SIZE OF CRYSTALLITES

The size of crystallites is measured with different gauged bolts. The distribution of mass vs size is determined.

We also showed that the average size of a particle only depends on the relative speed $\Delta v = v_i - v_h$ of the jet with respect to oil at the injector level; $\Delta v$ governs jet fracture.

The temperature difference $\Delta T_h = T_i - T_h$ which governs the aggregation between droplets (if $\Delta T$ is large there is no recombination; if $\Delta T$ is small, the coalescence is important)

The average size $\langle \phi \rangle$ is given by

$$\ln \langle \phi \rangle = (a + b\Delta T_h) + (c + d\Delta T_h) \ln \Delta v = A + B \ln \Delta v$$

where $a, b, c$ are constant and characteristic of the apparatus and of the liquids. Knowledge of $\langle \phi \rangle$ is important to calculate the efficiency as we shall see in the next paragraph.

4. HEAT TRANSFER EFFICIENCY

The efficiency coefficient $K$ is defined as the ratio of thermal power actually obtained $P_r$ to the thermal power $P_p$ which would be achieved had the exchange been perfect.

$$K = \frac{P_r}{P_p}$$

If $T_p$ is the final temperature of the mixture for perfect exchange

$$P_p = \psi_h \int_{T_h}^{T_p} C_h \, dT = \psi_i \left[ C_i (T_i - T_c) + L_c + C_s (T_c - T_p) \right]$$

with
- $C_i$ = molten salt heat capacity
- $C_s$ = solid salt heat capacity
- $C_h$ = oil heat capacity
- $L_c$ = melting latent heat

and

$$P_r = \psi_h \int_{T_h}^{T_m} C_h \, dT$$

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The direct determination of $K$ provides scattered points because of an important uncertainty, e.g. for $0.5^\circ$ in $T_h$ and $T_m$ and $1/\ell/m$ in flow, it reaches 15%. So we calculate $K$ by another way. Indeed we observe that oil-oil injection under the same conditions as with molten salt provides unit efficiency. So the apparatus is good and the differences from one are not due to the quality of exchange (thermal losses for instance). We admitted that the molten salt is not completely crystallized at the exit of the exchange column. Some quantity of molten salt remains inside the droplet and we assume they are at the melting temperature. Considering the average size it is possible to evaluate the average diameter of liquid phase and to know the energy still stored in a crystallite. Using $R = \frac{<\phi>}{2}$, $R_p$ : average radius for the liquid phase, $\rho_i$ : density of molten salt, we obtain for a perfect exchange

$$E_p = \frac{4}{3} \pi R^3 \rho_i \left[ C_L(T_i-T_c)+L_c+C_s(T_c-T_p) \right] = \frac{4}{3} \pi R^3 \frac{p}{\psi_i} \quad (4.4)$$

and for the energy not exchanged:

$$E_r = \frac{4}{3} \pi R^3 \rho_i \left[ L_c+C_s(T_c-T_p) \right] \quad \quad (4.5)$$

The efficiency is $K = \frac{E_p-E_r}{E_p}$ and the average size of a liquid part is:

$$\frac{<\phi_k>}{<\phi>} = \left[ \frac{1-K}{p} \right] \frac{p}{\psi_i(L_c+C_s(T_c-T_p))} \quad \quad (4.6)$$

The study of $<\phi_k>/<\phi>$ shows (fig.2) that this ratio only depends on $<\phi>$ with a good approximation. So from this graph we deduce $<\phi_k>$ for a measured $<\phi>$ and we calculate $K$ from (4.6).

5. INFLUENCE OF DIFFERENT PARAMETERS

As is usual in hydrodynamics this synthetic approach of problems requires dimensionless numbers. Let us start from Peclet's number:

$$P_e = \frac{\tau_{th}}{\tau_{ec}} = \frac{V}{\chi} \quad \quad (5.1)$$

(V : speed and $\chi$ : length of outflow, $\chi$ thermal diffusivity) which compares the characteristic times of thermal transfer and of flow if $\tau_{th} >> \tau_{ec}$ : the stay time of a drop is too short; it cannot give up all its heat

if $\tau_{th} << \tau_{ec}$ : the drop yields all its heat before it leaves the column.

But in the experimental case we have to take into account partial solidification. Applying Fourier's law to the heat flow through a drop of diameter $<\phi>$ we obtain:

$$\frac{dq}{dt} = \frac{\lambda(T_i-T_f)}{<\phi>} \cdot \frac{3 \rho_i C_L(T_i-T_c)+L_c+C_s(T_c-T)}{\psi_i} \cdot \frac{<\phi>^3 P_p}{\tau_{th}} \quad \quad (5.2)$$
and

\[ \tau_{th} = \frac{<\phi>^2 \rho_i \bar{P}}{\lambda_i (T_i - T_p)} \]  (5.3)

The number characteristic of this phenomenon is

\[ P' = \frac{\rho_i <\phi>^2 <v> P}{\lambda_i i (T_i - T_f)^i} \]

The variations of \( K \) vs. \( P' \) are represented on fig. 3. It shows that with an excellent precision \( K \) only depends on \( P' \). As expected the efficiency is good when \( P' \) is small.

6. CONCLUSION

It must be noticed that it is possible to realize a dynamical exchanger at direct contact with very good efficiency. All the experimental results can be correlated with a single dimensionless number, giving the efficiency of the apparatus. One may achieve a genuine optimization of the system and carry out an a priori calculation of the characteristics of an exchanger.

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FIGURE 1: Schema of apparatus

FIGURE 2: Variation of diameter of liquid core as a function of average diameter of a drop.

FIGURE 3: Variation of efficiency $K$ as a function of the dimensionless number $Pe'$. 

\[ T_h = 70 \, ^\circ C \]
\[ T_h = 80 \, ^\circ C \]
\[ T_h = 100 \, ^\circ C \]
\[ T_h = 110 \, ^\circ C \]

\[ \Delta T_h = 72^\circ C \]
\[ \Delta T_h = 62^\circ C \]
\[ \Delta T_h = 50^\circ C \]
\[ \Delta T_h = 32^\circ C \]