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TIME DEPENDENT HEAT STORAGE CAPACITY FOR LATENT COLD STORE

BY

Aboul-Enein, S. and Olofa, S.A.

Physics Department, Faculty of Science, Tanta University, Egypt

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ABSTRACT

The influence of the mass flow rate and the driving temperature difference on input/output rate, the total time and the storage capacities during charging and discharging of the latent cold store for different initial and boundary conditions was investigated. The latent store was filled with caprilic acid (m.p=15.5 ^{0}C). At given time the charging and discharging rate, and the storage capacity are higher for higher mass flow rate. The total storage capacity is a function of the temperature swing experienced during charging and discharging. The experimental data are in good agreement with the calculations, within ± 10% if the heat loss/gain is accounted for. A good agreement was obtained, when the experimental heat capacity values in dimensionless form were compared with the theoretical data according to Steiner [4] for charging and discharging.

INTRODUCTION

The basic characteristics of all latent heat/cold stores are the addition of energy during charging and release of energy during discharging. The latent heat/cold energy storage concept has the primary advantage of performing the storage function at nearly constant temperature and large storage capacity.

Charging and discharging of latent heat/cold storage systems are transient phenomena which are influenced by design of heat exchanger, type and geometry of the storage material, initial and boundary conditions, etc.

Analytical and numerical solutions of mathematical models describing the charging and discharging of latent heat storage systems have been made [1-3]. These methods require detailed information of the thermophysical properties of the phase change material(PCM).

For simulation of latent heat/cold stores a black-box-approach is used and assessment of the store behaviour is based on the actual time-dependent storage capacity [4]. The work described here is confined to the evaluation of the time dependent heat storage capacity of the finned annulus test model filled with a PCM for cooling applications. The influence of mass flow rate ($\dot{m}$) and the driving temperature difference (ΔT_p) on the input/output rates, the total time and the storage capacity as function of time during charging and discharging for different initial and boundary conditions were investigated. A mathematical function with two fitting parameters is used to describe the dimensionless storage capacity of the considered thermal store.

THE TEST MODEL

The test model is an axially finned annulus tube, made of aluminum (length=100 mm, outer tube diameter=110 mm, 12 fins with fin thickness 2mm) filled with caprilic acid (0.75 kg in weight). The flow rate of the circulating fluid was measured using a flowmeter type Krohne G 19.18. The flowmeter was calibrated, to give the mass flow rate in kg/h at any required temperature of the fluid, with an error of ± 0.5 kg/h. The temperature rise or fall ($T_{in}-T_{out}$) experienced by the circulating heat transfer fluid was measured using a Servogor 320-2-Channel continuous strip chart recorder. The test runs were carried out using the calorimeter mounted on the inner tube ,and the calorimeter mounted on the outer tube.Figure (1) shows a photograph of the test assembly, while Figure (2) represents a schematic diagram showing the test model and the other instrumentations used in the test. More details on the dimensions and instrumentation of this test model are given in [1,5].

MATHEMATICAL MODEL

The driving temperature difference ΔT_p is defined as the temperature difference between the inlet temperature of the circulating fluid T_{in} and the melting or freezing point T_m. The heat flow rates during charging($\dot{Q}_c$)and discharging($\dot{Q}_d$)are given as follow:

$$\dot{Q}_c(t) = \dot{m}\, C_p(\, T_{out} - T_{in}) \qquad (1)$$

and

$$\dot{Q}_d(t) = \dot{m}\, C_p(\, T_{in} - T_{out}) \qquad (2)$$

where $\dot{m}$ is the mass flow rate of the heat transfer fluid, C_p is its specific heat,T_{in} and T_{out} are the inlet and outlet temperature respectively.

The heat storage capacity can be obtained by integrating equations (1) and (2) with respect to time,and taking the heat losses into account.Then for charging,the storage capacity C_c

is given by [4],

$$C_c(t) = C_0 + \int_{t_c=0}^{t} \dot{Q}_c(t)\,dt \pm \int_{t_c=0}^{t} \dot{Q}_{L,c}(t)\,dt \qquad (3)$$

and for discharging the capacity C_d is given by

$$C_d(t) = C_{max} - \int_{t_d=0}^{t} \dot{Q}_d(t)\,dt \pm \int_{t_d=0}^{t} \dot{Q}_{L,d}(t)\,dt \qquad (4)$$

where C_0 is the initial storage capacity at $t_c=0$ (before charging) which is equal to the final storage capacity at $t_d=\tau_d$ (at the end of discharging),and C_{max} is the final storage capacity at the end of charging,i.e at $t_c=\tau_c$ and it is equal to the initial storage capacity at $t_d=0$.

In equations (3) and (4) $\dot{Q}_{L,c}$ and $\dot{Q}_{L,d}$ are the heat loss rates during charging and discharging respectively, and the ± signs have to be used for $T_{store} \gtrless T_{ambient}$.

The experimental values of heat flow rate $\dot{Q}$,heat losses, and the heat capacity C for all the charging and discharging runs were assessed using the IKE computer programs which are based on the previous equations[6].

A modified exponential function based on the kinetics of phase change ,was derived[4]:

$$C_c(t^*) = [\,1- \exp\{-N.(t^*)^N\}]/[\,1- \exp(-N)] \qquad (5)$$

for charging and,

$$C_d(t^*) = 1 - [C_c(t^*)] \qquad (6)$$

for discharging.In equations (5) and (6) C^* is the dimensionless storage capacity = $C(t)/C_{max}$, t^* is the

Delta J. Sci. 17 (3), 1993
S. Aboul-Enein

dimensionless time = t/τ_{tot} and τ_{tot} is the charging/discharging time. The exponents M and N depend on the latent heat storage system design and type, the phase change material and operation conditions. They are fitting parameters defined in the range $0 < M \leq 1$, $N > 0$.

The data obtained for charging and discharging at different operational conditions are analyzed and then fitted to equations (5) and (6) using the IKE computer program developed for such analysis [6].

RESULT AND DISCUSSION

1. The heat transfer rate

The charging and discharging rates obtained only for convective boundary condition.In this case the rate of heat transfer is time dependent and is essentially governed by the mass flow rate ($\dot{m}$) and the driving temperature difference ΔT_p. The heat transfer coefficient between the circulating fluid and the thermal store, is a function of the mass flow rate. The heat transfer rate during all the test runs were computed using the equations (1) and (2). Figures (3) and (4) represent the influence of the mass flow rate on the charging (freezing) and discharging (melting) rates using the outer tube calorimeter for constant value of ΔT_p. At the beginning of charging or discharging a higher rate of heat transfer was obtained for higher mass flow.This is due to the improvement of the heat transfer coefficient at the outer tube wall of the test model at higher flow velocities. With increasing time, the higher mass flow result in faster cooling/heating of PCM and the charging/discharging process is completed in shorter time. For the same boundary conditions the heat transfer rates during melting are higher than during freezing due to the buoyancy forces and the convection effects in the test model during melting [8].

Figures (5) and (6) show the influence of ΔT_p on the discharging rate using the outer and the inner tube calorimeter respectively at constant value of m. Three runs were carried out using each calorimeter at three different values of ΔT_p, viz. 10, 15 and 20 K. The discharging rates are higher for higher ΔT_p values. Using the outer tube calorimeter the discharging rates (fig.5) were higher than when using the inner tube calorimeter, that is due to the relatively larger heat transfer area of the outer tube.

2.The total charging and discharging times

The charging and discharging runs started from a steady state where the temperature in the test model was kept at constant value (the initial temperature). At the end of the run and after reaching a steady state, the total charging or discharging time τ_{tot} was measured.

Figure (7) shows the relation between ΔT_p and the τ_{tot}, using the inner tube calorimeter of two constant values of the mass flow rate of 4.3 kg/h and 9 kg/h. The initial temperature of the store was 30^0C.The total charging time decreases with increasing ΔT_p.

Figure (8) represents the effect of the mass flow rate (m) on the total charging time τ_{tot} for different values of ΔT_p, using the outer tube calorimeter.The total charging time

Delta J. Sci. 17 (3), 1993
S. Aboul-Enein

is indirectly proportional to the mass flow rate.

3.The charging and discharging capacities

Figure (9) represents the dependence of the charging capacity on time for three charging runs, performed for three different values of mass flow rate(4.3 kg/h,9.4 kg/h,19.4 kg/h). The initial heat store temperature was 35^{0}C. At any given time, the charging capacity is higher for higher mass flow rates which results in higher rate of charging and consequently a higher capacity. The storage capacity is a function of the temperature swing (ΔT_{i-f} = $T_{initial}$ − T_{final}) experienced during charging process, which is constant (about 40 K) for the three runs. The end capacities are therefore nearly the same, within ± 10 % if the heat losses are accounted for.

Figure (10) represents the variation of the discharging capacity with time for three discharging runs, carried out at different values of the mass flow rate (9.6 kg/h,19.9 kg/h, 38.7 kg/h). The initial heat store temperature was - 5 ^{0}C. The higher discharging capacity is associated with higher mass flow rates. The total capacity at the end of all the discharging runs is nearly the same if the heat losses or gains are considered (depending on the temperature level within the heat store at any time during the charging process) . It agrees with the maximum charging capacity,see fig.(9), within the heat loss limits. Also it is noticed that the maximum heat storage capacity for charging and discharging is attained a longer time in case of lower rate

Figure (11) shows the relations between the discharging capacity and time of three discharging runs performed at three driving temperature difference (ΔT_p). The initial heat store temperature was - 5^{0}C. The discharging capacity at any given time is higher for higher values of ΔT_p. This result is in close agreement with the theory (where the heat storage capacity is a function of the temperature swing experienced).

Figure (12) represents the heat storage capacity (theoretically estimated as well as experimentally determined) as a function of the temperature swing experienced during charging and discharging. The experimental data are in good agreement with the calculations.The latent heat capacity of storage medium in the test model was found to be 112 kj for 0.75 kg caprilic acid, which gives the value of 149.3kj/kg for latent heat of fusion of this material. The value obtained is in close agreement with the measured using the DSC [7].

4.Dimensionless storage capacity

Figures (13) and (14) represent comparison between the experimental and the theoretical dimensionless storage capacity C^* and the dimensionless time t^* during charging and discharging runs from the inner and outer tube calorimeter respectively.

In fig.(13) the experimental results are in good agreement with the theoretical results from equations (5) and (6), where the fitting parameters M and N are adjusted to 0.75 and 0.15 for charging and 0.78 and 1.08 for discharging respectively.

In fig.(14) the experimental results are also in good agreement with the theoretical data obtained from equations

(5) and (6), where the fitting parameters M and N were adjusted to 1 and 2.43 for charging and 1 and 2.55 for discharging respectively.

CONCLUSION

With the laboratory finned annulus test model filled with caprilic acid (mp = 15.5°C) as latent cold storage material, the charging and discharging capacities (included the thermal loss/gain) were experimentally investigated and then calculated using the IKE simulation program [6]. The influence of the mass flow rate (m) of the circulating heat transfer fluid and the driving temperature difference (ΔT_p) on heat transfer rate, the total time and the storage capacity was studied during charging and discharging at different initial and boundary conditions. The charging capacity is higher for higher mass flow rate. It was found that for a temperature swing of 40 K (ΔT_{i-f}= 40 K) the test model can store about 250 kj. From the charging and discharging runs carried out for different temperature swings from 20 - 50 K,a value of 149.3 kj/kg for the latent heat of fusion of caprilic acid was obtained from the storage capacity,this is in close agreement with the value measured (150.4 kj/kg) using the DSC for caprilic acid [6].

A good agreement was maximum deviation of ± 0.5% obtained, when the experimental capacity values in dimensionless form were compared with the theoretical data according to Steiner et al. [4] for charging and discharging.

ACKNOWLEDGMENT

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Delta J. Sci. 17 (3) 1993

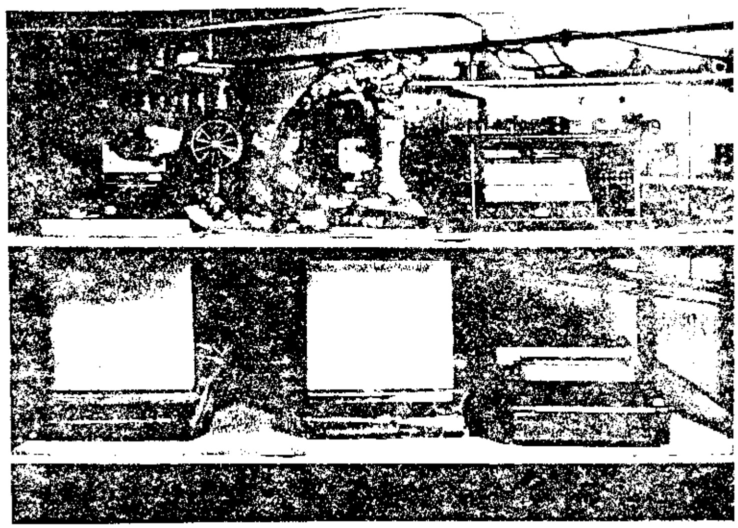

Fig. 1 Photograph of test assembly

Delta J. Sci. 17 (3) 1993

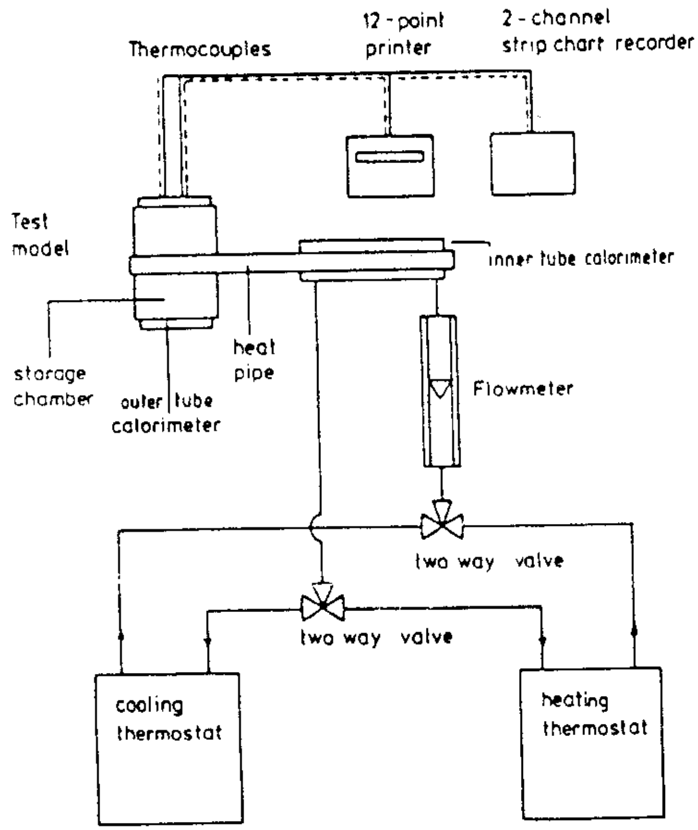

Fig. 2 A Schematic diagram showing the test model and the other instrumentation used in the tests

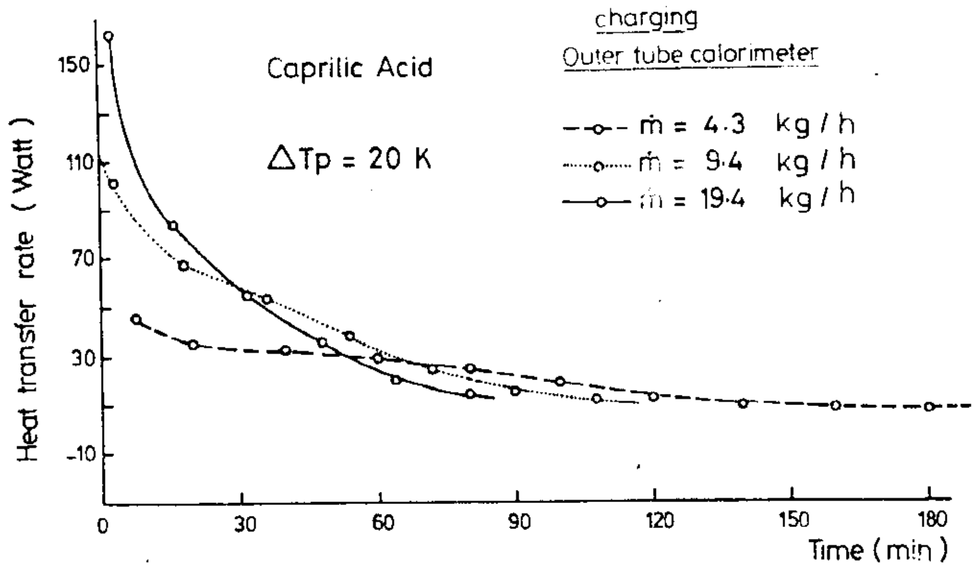

Fig. 3 Influence of mass flow rate ṁ on the charging rate using the outer tube calorimeter

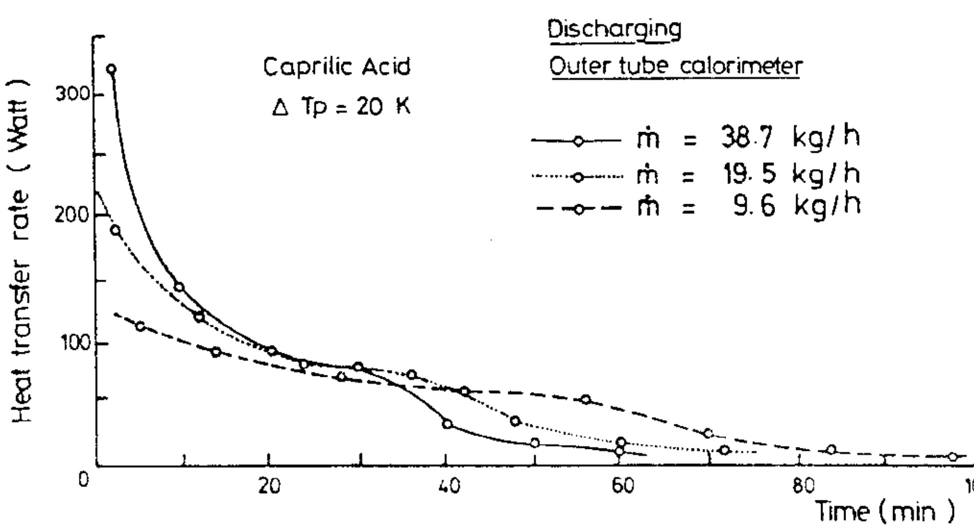

Fig. 4 Influence of mass flow rate ṁ on the discharging rate using the outer tube calorimeter

Delta J. Sci. 17 (3) 1993

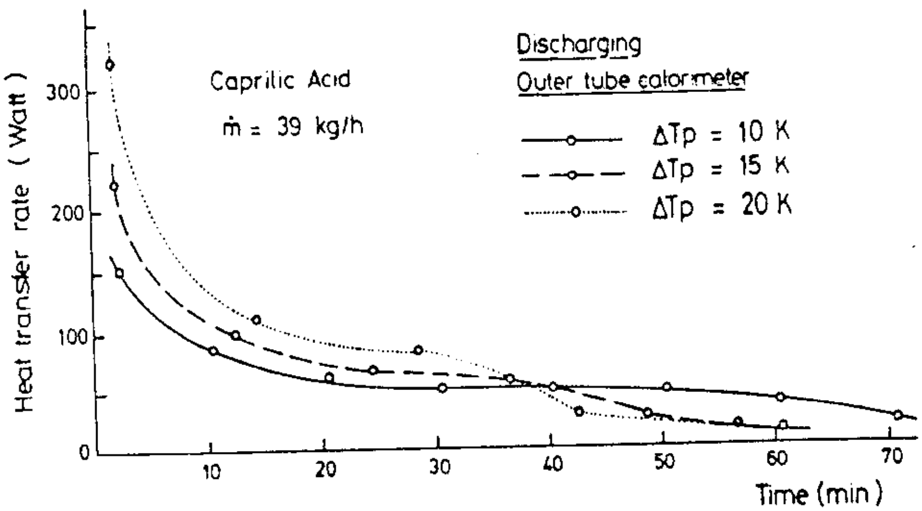

Fig. 5 Influence of ΔTp on the discharginging rate using the outer tube calorimeter

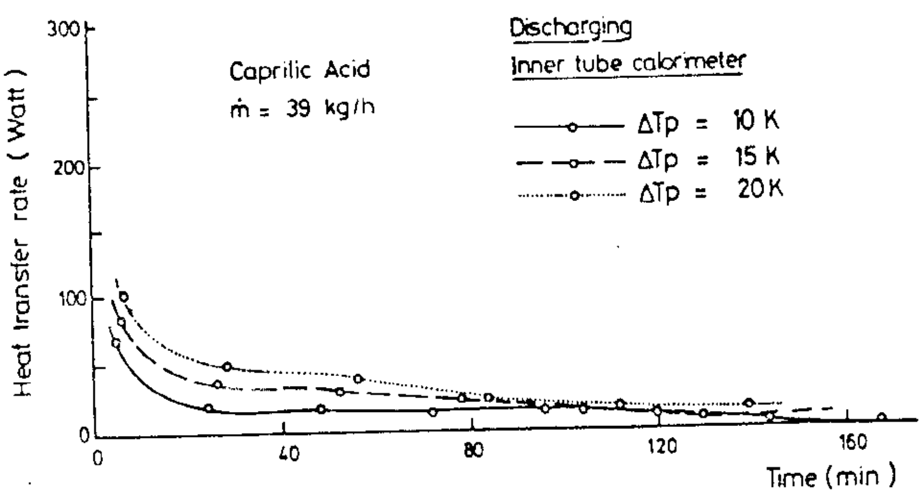

Fig. 6 Influence of ΔTp on the discharging rate using the inner tube calorimeter

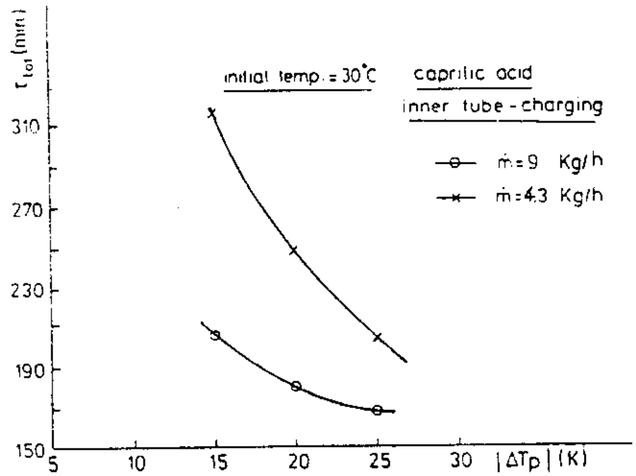

Fig 7 The effect of |ΔTp| on the total charging time using inner tube calorimeter in the test.

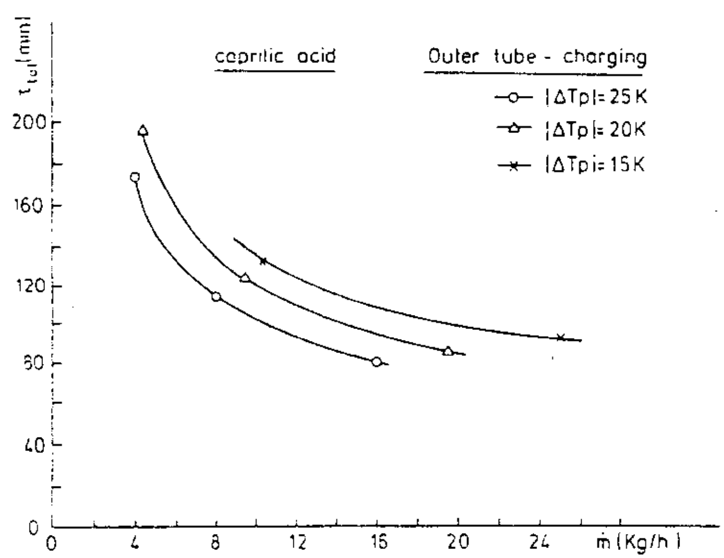

Fig 8 The effect of mass flow rate (ṁ) on the total charging time τ_{tot}, using the outer tube calorimeter in the test.

Delta J. Sci. 17 (3) 1993

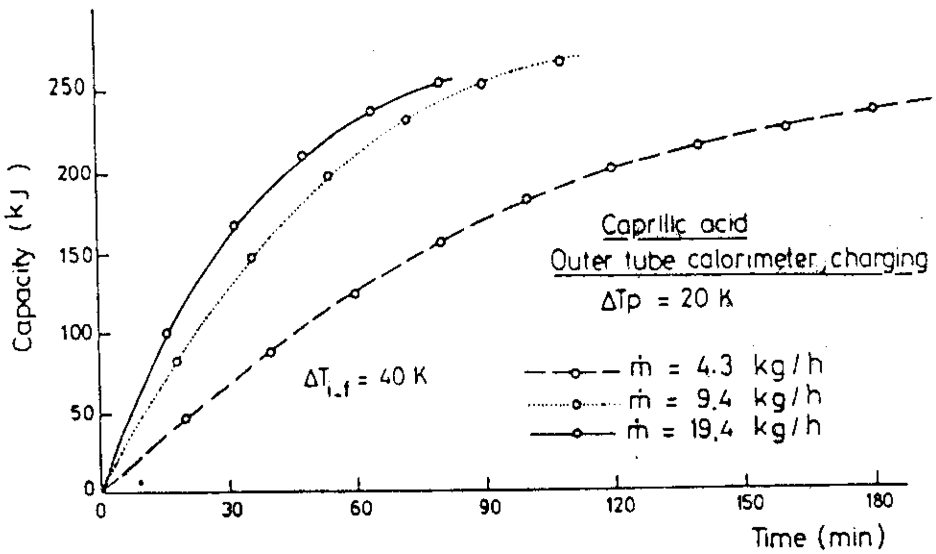

Fig. 9 Influence of mass flow rate on the charging capacity using the outer tube calorimeter

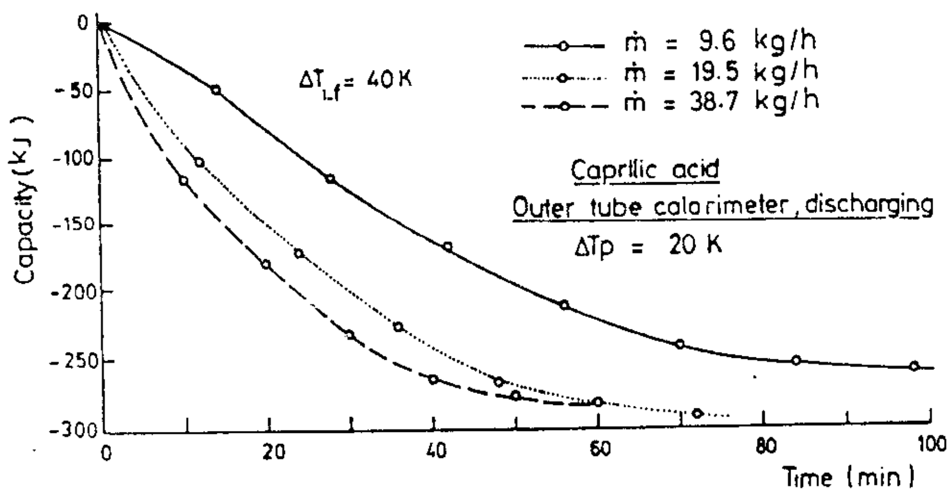

Fig. 10 Influence of mass flow rate on the discharging capacity using the outer tube calorimeter

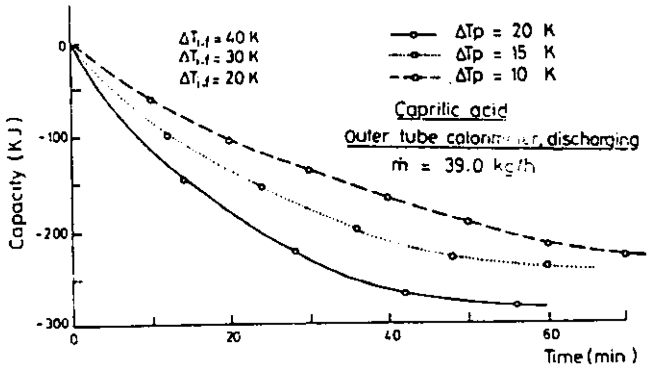

Fig. 11 Influence of ΔTp on the discharging capacity using the outer tube calorimeter.

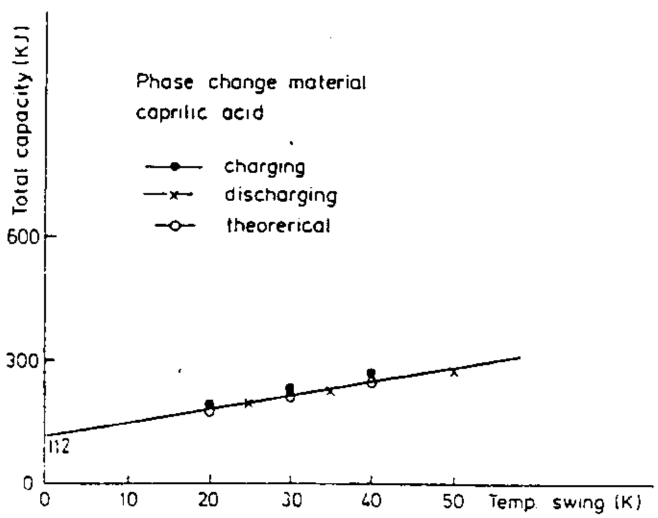

Fig. 12 Computed and experimentally determined values of the total storage capacity of the test model filled with capritic acid

Delta J. Sci. 17 (3) 1993

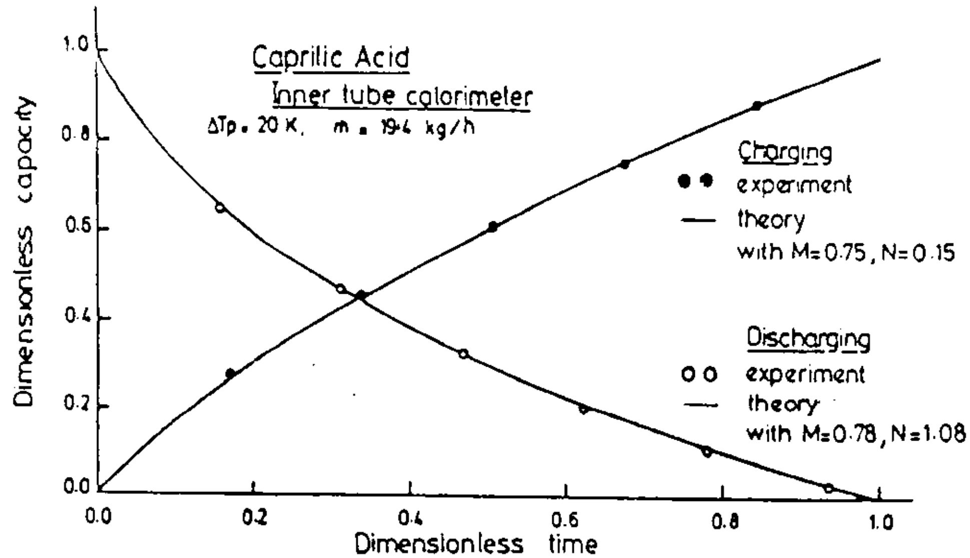

Fig. 13 Dimensionless capacity vs dimensionless time for charging and discharging by the inner tube calorimeter

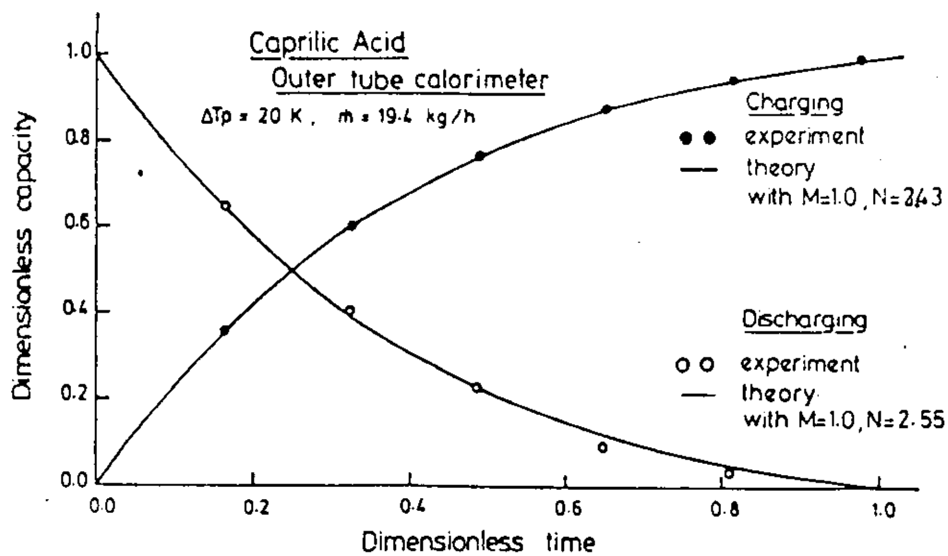

Fig. 14 Dimensionless capacity vs dimensionless time for charging and discharging by the outer tube calorimeter

Delta J. Sci. 17 (3) 1993

السعه الحراريه المتغيره زمنياً لمخزن البروده الكامنه

سعد أبو العينين - السيد أحمد علوفه
قسم الطبيعه - كلية العلوم - جامعة طنطا

أجريت قياسات لدراسة تأثير بعض العوامل على كفاءة وسعة تخزين وكذلك معدل إنتقال البروده من وإلى مخزن البروده الكامنه أثناء شحنه وتفريغه (أثناء تجمد وإنصهار مواد فى المدى من صفر - ٢٠ م) وذلك عند ظروف معمليه معمليه مختلفه . وقد وجد أن معدل إنتقال البروده من وإلى المخزن يزداد بزيادة معدل سريان المائع الناقل للبروده وكذلك فروق درجات الحراره بين المخزن والمائع . وقد قورنت القياسات العمليه بالحساب النظريه وكانت متطابقه أثناء شحن وتفريغ المخزن عندما أخذت فى الإعتبار نسبة الفقد (loss / gain) فى البروده والتى قدرت بحوالى ±١٠٪ . كما قورنت قياسات السعة الحراريه المتغيره زمنياً أثناء الشحن والتفريغ بنموزج Steiner النظرى على الحاسب الألى وكانت السعة الحراريه المقاسه عملياً متطابقه مع النتائج النظريه