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HEAT TRANSFER AND INTERFACE MOTION DURING MELTING AND FREEZING IN FINNED ANNULUS FOR LATENT COLD STORAGE SYSTEM

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ABSTRACT

Experiments were performed to study melting and freezing characteristics in finned annulus for latent cold applications.Three different phase change materials (melting range 0 - 20^0C)were selected. They are decanol, caprilic acid and hexadecane. The solid-liquid interface position during phase change was recorded photographically and the temperature distribution for different initial and boundary conditions was measured.A small amount of supercooling ($\leq$ 0.5 K) was observed during freezing of caprilic acid. The effect of the mass flow rate and the driving temperature difference on the melting and freezing time were studied.During melting natural convection and gravity force aid in improving the heat transfer rate. The effectiveness of fins is greatest during freezing. The presence of natural convection in melt retarded freezing only by little amount. Freezing was seen to be associated with formation of denderities or whisker-like crystal similar to those reported in [7,8],which improved the freezing rate. The critical Rayleigh number Ra, which controls the natural convection lies between $1.6\times10^7 \leq Ra \leq 2.5\times10^7$ in the test model.

INTRODUCTION

Heat transport during solid-liquid(melting) and liquid-solid (solidification) phase change plays an important role in numerous naturally and technical processes.In many technical areas such as casting technology,thermal energy storage design, welding and nuclear power,knowledge of the governing hydro-and thermodynamic phenomena is of great importance[1].

In the past most analyses dealing with phase change problems have taken into account heat conduction as the sole heat transfer mechanism.Physical situation,however,in which heat conduction acts alone during phase change -in the phase change material (PCM) - will not often be observed,because even small temperature variations in the melt can activate natural convection flow due to buoyancy forces. This effect in turn violates the existing temperature distribution and can amplify the strength of heat transfer characteristics.This interaction between two of the basic heat transport mechanisms is quit evident,when melting processes in latent heat-of-fusion thermal energy systems are investigated.

Available experiments data [2-3] have established that during melting natural convection in the liquid aids heat transfer. However during freezing the development of natural convection in the melt can greatly reduce and even stop the process if the liquid is superheated[5].In addition, the layer formed on the cooled surface increases the thermal resistance and can greatly reduce the heat transfer rate particulary for materials that have low thermal conductivity.

A standard method to enhance heat transfer,if the dominate resistance is on the fluid side, is to use extended surfaces [4-5]. The use of fins to enhance heat conduction in latent heat-of-fusion energy storage systems has been reported [6-8].

The work described in this paper is confined to the heat transfer and the interface motion during meting and freezing for different boundary conditions in finned annulus for latent cold storage applications.The effect of the mass flow rate and the driving temperature difference on the melting and freezing time will be studied. The concept of finned annulus heat exchanger for passively operating latent heat store has been presented and optimized earlier by Aboul-Enein [8].

EXPERIMENTS

The test model: The test model used for the experimental invesitigation is the finned annulus laboratory test model.It consists of an heat pipe (acting as inner tube) and an outer tube maintained in thermal contact with each other through longitudinal fins (12 fins) made from good heat conducting material .The fins are welded (electron beam welding) with the inner and outer tube to insure a good thermal contact .The various segments are interconnected through holes drilled in the fins separating the segments. The free volume between the fins is filled with the desired PCM.Heat input to the storage chamber or out of it was achieved by mounting a calorimeter at the evaporator end of the heat pipe. Another calorimerter was mounted on the wall of the outer tube to realize also the possibility of charging or discharging through it.

The circulating heat transfer fluid used for freezing or melting of the PCM is di-ethylene-glycol ethyelether ($C_6H_{14}O_3$) trade mark 30/100.This fluid is suitable for use in the range of temperature from (-30 to 100^{0}C).

The test model was instrumented with 8 NiCr-Ni thermocouples to obtain information regarding the temperature distribution in the PCM within the storage chamber,along the heat pipe wall,room temperature and in the inlet and outlet lines of the fluid circulating in the calorimeters. The location of thermocouples are shown in figure (1). All thermocouples used were delivered from the manufacturer as calibrated with maximum error of± 0.5 K.

TEST PROCEDURE

At any given time during the melting and freezing runs,temperature at all given selected points were measured using a Philips PM 8235 12-point printer with an error of ±1 K. The fluid flow rate was measured using a variable area flowmeter type Krohne G19.18.The flowmeter and the circulating fluid was from Schlieter-Lab,Stuttgart.The test procedure was according to IKE recommendation[10].

In all the freezing and melting runs and prior to the start of the test,the temperature of the PCM was uniform at the required temperature.Photographs of the motion of the solid-liquid interface during freezing and melting were taken through the transparent plexiglas flange closing the front of the storage chamber.For temperature distribution measurements the test model was filled with caprilic acid, while for photographs of the motion of the interface it was filled with decanol. Both of these materials are good candidates for latent cold storage systems[11].

A transient charging or discharging is initiated by a"positive" or "negative" step of the inlet temperature of the heat transfer fluid.The driving force for charging or discharging of the heat store is the driving temperature difference which is defined as $\Delta T_p = T_{in} - T_m$, where T_m is the melting or freezing point of the PCM and T_{in} is the inlet temperature.

RESULTS AND DISCUSSION

1. The temperature distribution during charging discharging

During melting and freezing of the PCM in the test model, the temperature variation depends on the radial, azimuthal positions and time.There are three thermocouples (1,2,3) located radially in different positions along the z-z axis of the test model (fig.1) at 8 mm,38 mm and 55 mm respectively in the storage chamber and in the lower middle segment of the model.The test model was filled with caprilic acid (m.p=15.5^{0}C) then it was well insulated.

Figures (2) and (3) present the temperature distribution inside caprilic acid at different times during freezing using the inner tube and the outer tube calorimeter respectively.The initial temperature of the PCM was 34^{0}C.From the figures it is obvious that the thermocouple number 2 (TC2) is the last one to record freezing, so that the temperature of that thermocouple serves as an indication of complete freezing of the material.

Figures (4) and (5) show the temperature distribution inside caprilic acid at different times during melting, using the inner tube calorimeter. TC2 is the last one indicate melting of the material, so that its temperature serves to indicate the complete melting.

The figures from (2) to (5) provide indirect knowledge of the phase interface position during melting and freezing of the PCM. On the other hand, the charging and discharging history of the three PCM used in the test model is presented in figures (6,7) As seen in these figures the melting and freezing curves can be subdivided in three regions.Regions I,II and III differentiated by the slope of the curves.Region II marked by a flat temperature profile of TC2.The time corresponding to region II is the melting or freezing time.

From figures (6,7) it is clear that decanol has the phase change range between 3.5 - 5.5 ^{0}C,and caprilic acid has the phase change range between 13.5 - 15.5 ^{0}C,whereas hexadecane exhibits solid liquid phase transition at 18 ^{0}C.There are no supercooling effects seen for decanol and hexadecane, while an small amount of supercooling (≤ 0.5 K) is observed during the freezing of caprilic acid (fig 6).The results obtained for the three materials were fairly good compared with those measured by DSC [9,11].

2.Melting and freezing time

The melting and freezing time is defined as the time during which complete phase transition occurs in the test model as indicated by all thermocouples from the beginning to the end of phase change.

The effect of the mass flow rate m and the driving temperature difference ΔT_p on the melting and freezing time is shown in figures (8 -11) at different initial and boundary conditions. It is noticed that the melting and freezing times are roughly inversely proportional to $\dot{m}$ and ΔT_p.Besides,the large area of the outer tube through which heat exchange takes place during melting and freezing when using the outer tube calorimeter results in shortening the melting and freezing times compared to the inner tube calorimeter tests.

3. Visual and photographic observations

The freezing process was performed using the outer tube calorimeter and the melting process using the inner tube calorimeter. Qualitatively these photographs show the various physical effects occurring during heat transfer inside the test model and indicates the position of the solid-liquid interface with time. Quantitatively the photographs provide information on the fraction of the molten and solidified phases at any time.

a. Melting

Figure (12) shows a sequence of photographes taken during melting of decanol,using the inner tube calorimeter.The driving temperature difference ΔT_p for this melting run was 16.5 K and the mass flow rate($\dot{m}$) of the circulating fluid was 18 kg/h.

Photograph (1) shows the starting condition.The PCM is solid at a temperature of -11^{0}C.Addition of heat results at first in uniform heat transfer in all segments,as depicted by the position of the solid-liquid interface (photographs 2,3). The heat transfer until now is by conduction in all segments.As melting proceeds natural convection from the hot wall of the inner tube sets in improving the rate of heat transfer in the segments of the upper hemisphere.Gravity forces thus aid in improving the heat transfer rate due to direct contact between the solid phases and the metallic walls (photograph 4).With time,gravity forces assist in the vertical fall of the solid decanol in other segments too,bringing it in contact with the hotter metallic walls.This improves heat transfer in the other segments as shown in photographs (5,6).

b. Freezing

The photographs in figure(13) were taken for a freezing run carried out for $\dot{m}$ = 11.4 kg/h and ΔT_p =15 K.The temperature of the PCM in the liquid phase at the start of the experiment was 20°C.

The photographs indicate that freezing of the liquid material occurs in the lower hemisphere faster than that in the upper hemisphere only at the beginning of freezing (photographs 1 to 4).The metallic fins assist in suppressing convection during freezing.It was seen that freezing was associated with the formation of denderities or whisker-like crystal, similar to those reported in [7,8].

The Rayleigh number,Ra,the dimensionless parameter controlling the natural convection in the test model based on the equivalent length(l_{eq})is defined as: $Ra = g\beta \, \Delta T \, l_{eq}^{3}/\nu \, a$,where g is the acceleration of gravity, β is the thermal expansion coefficient, ν is the viscosity,and a is the thermal diffusivity . For the present work the values of Ra number lies between $1.6*10^7 \leq Ra \leq 2.5*10^7$,when the test model is filled with decanol as PCM. These values are in good agreament with the given values in the lituratures.

CONCLUDING REMARKS

Experimental investigations of melting processes in the finned annulus show clearly that only in the earliest of the process the heat transport mechanism is due to conduction alone,where as natural convection flow is activated due to buoyancy and gravity forces. Photographs and visual observation demonstrate this fact. It can be observed that the melting front moves faster in the upper hemisphere than the lower hemisphere of the finned annulus. This different shapes of the melting interface resulted inspite of similar initial and boundary conditions. The effectivess of fins is greatest during solidification at early times when the frozen layer formed on the heat sink is thin and decreases as the layer grows thicker.The presence of natural convection in the melt retarded freezing only by relatively little amount due to the effectiveness of fins.During freezing the metallic fins assist in suppressing convection. Freezing was seen to be associated with the formation of denderities or whisker -like crystals,similar to those reported in [7,8],which improves the freezing rate.The critical Rayleigh number Ra in the test model, when it filled with decanol, lies between $1.6*10^7 \leq Ra \leq 2.5*10^7$.

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REFERENCES

[1] Rieger, H., Projahn, U., and Beer, H.,"Analysis of the heat transport mechanisms during melting around a horizontal circular cylinder"Int.J.of Heat and Mass Transfer, Vol. 25, no. 1, pp 137-147 (1982).

[2] Sparrow,E.M.,Shmidt,R.and Ramsy,J.W.,"Experiments on the Role of Natural Convection in the Melting of Solids" ASME J. of Heat Transfer vol. 100 (1978).

[3] Sparrow, E. M., Ramsy, J. W., and Kemink, R. G.,"Freezing Controlled by Natural Convection" ASME J.of Heat Transfer vol.101 (1979).

[4] Ekert, E. R. C., and Drake, R. M.,"Analysis of Heat and MassTransfer", Mc Graw-Hill, New York (1972).

[5] Bathelt, A.G. and Viskanta,R.,"Heat Transfer and Interface Motion during Melting and Solidification around a finned Heat Source/Sink ",Transactions of the ASME ,J. of Heat Transfer,vol 103 (1981).

[6] Henze,R. and Humphrey,J.A.C.,"Enhanced Heat Conduction on phase Change Thermal Energy Storage Devices" ASME paper no. 80-WA/HT-45 (1981).

[7] Sparrow,E.M.,Larson,E.D.,and Ramsy J.W.,"Freezing on a Finned Tube for Either Conduction-Controlled or Natural Convection-Controlled Heat Transfer",Int.J. of Heat and Mass Transfer vol. 24 (1981).

[8] Aboul-Enein,S.,"Waermeuebertragung in einem Latent-Waermespeicher mit beripptem Ringspaltrohr - Waermeaustauscher " Ph.D. Thesis,University of Stuttgart,W.Germany (1982)

[9] Olofa,S.A ,"Investigation of Heat Storage Materials for use in Solar Energy Applications" Ph.D.Thesis,Tanta University ,Tanta, Egypt (1987).

[10] Forschungsvorhaben BMFT 03E-8007-A"Pruefstand fuer Latentwaermespeicher,Phase 1" Bricht Nr.,IKE-5TF -609-84,IKE,University of Stuttgart,.Germany (1984).

[11] Aboul-Enein,S.,and Olofa,S.A."Thermophysical Properties of Heat-of Fusion Storage materials for Cooling Applications", Renewable Energy vol. 1, No. 5/6, pp. 791-797 (1991).

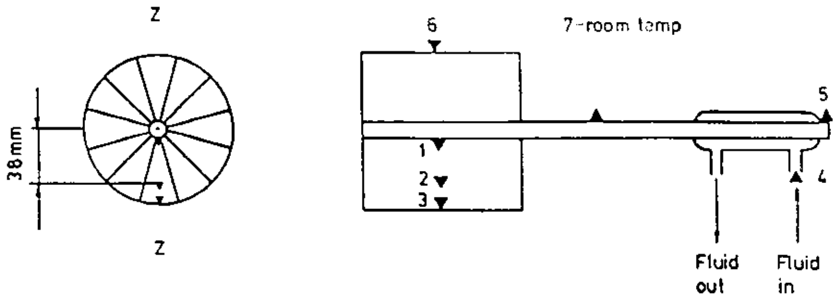


Fig. 1 Location of thermocouples in the test model.

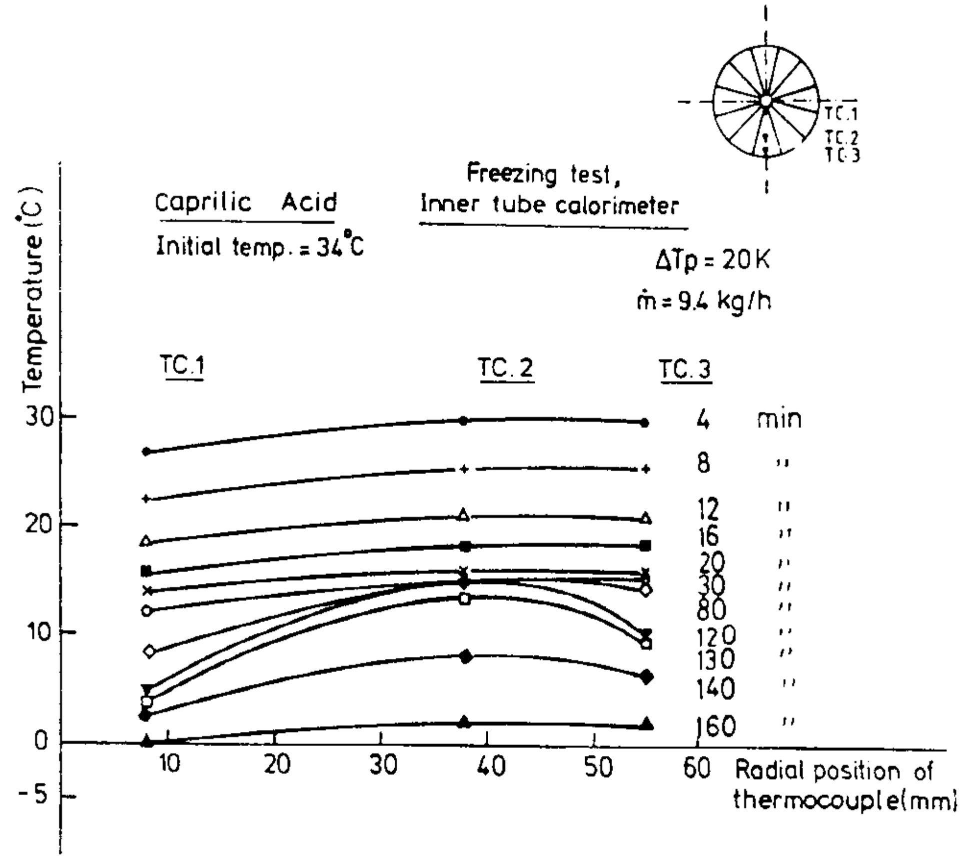


Fig. 2 Temperature distribution inside caprilic acid at different times during freezing, using the inner tube calorimeter

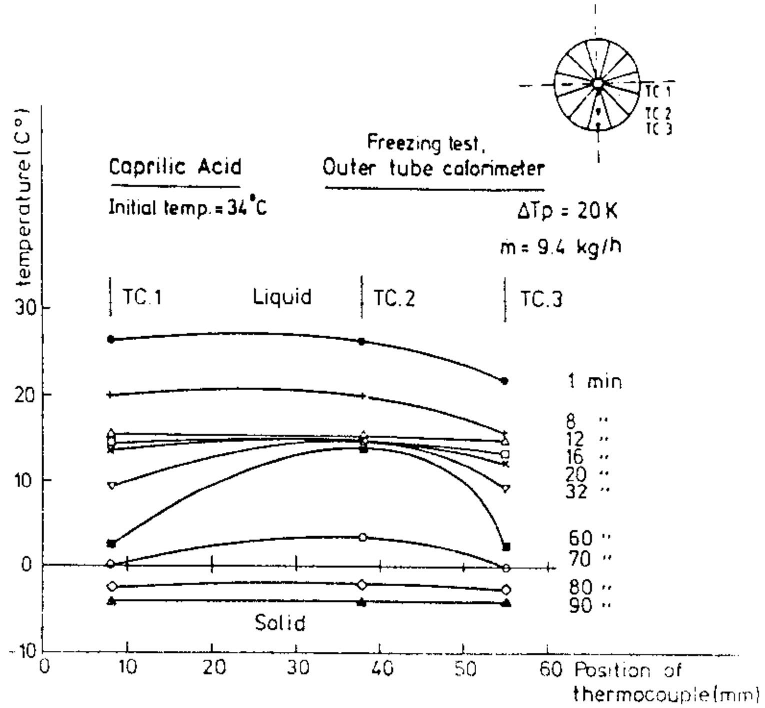


Fig 3 Temperature distribution inside caprilic acid along the Z-Z axis at different times during freezing, using the outer tube.

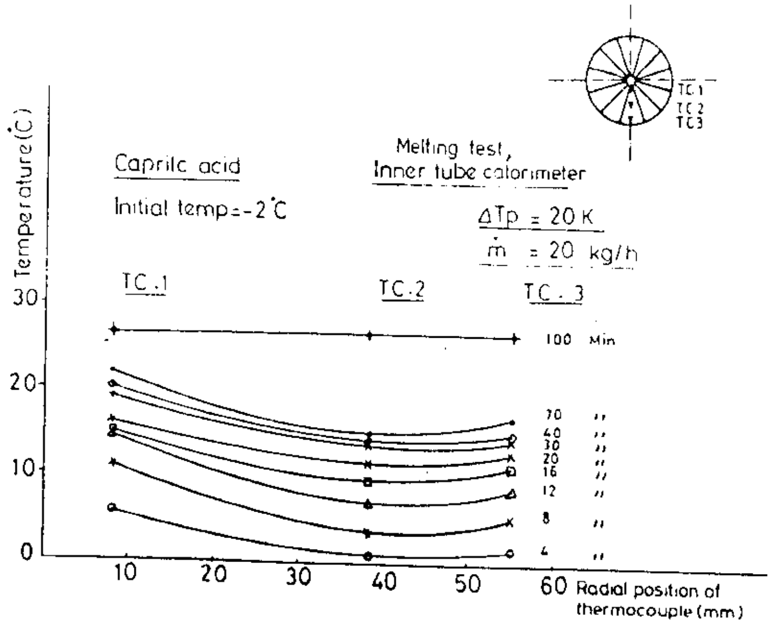


Fig. 4 Temperature distribution inside caprilic acid at different times during melting, using the inner tube calorimeter

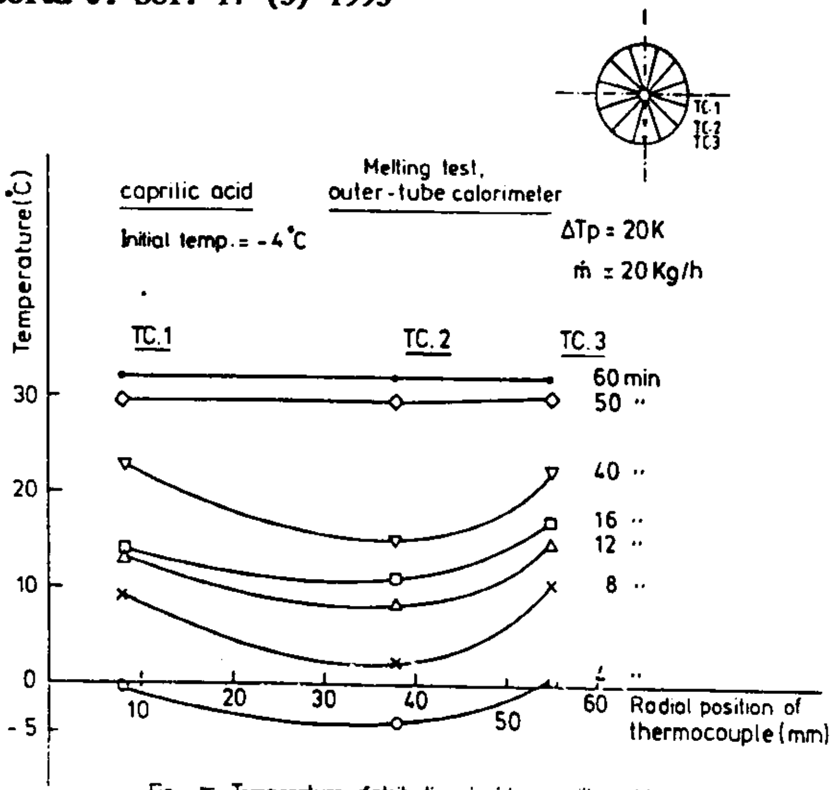


Fig. 5 Temperature distribution inside caprilic acid at different times during melting, using the outer tube calorimeter

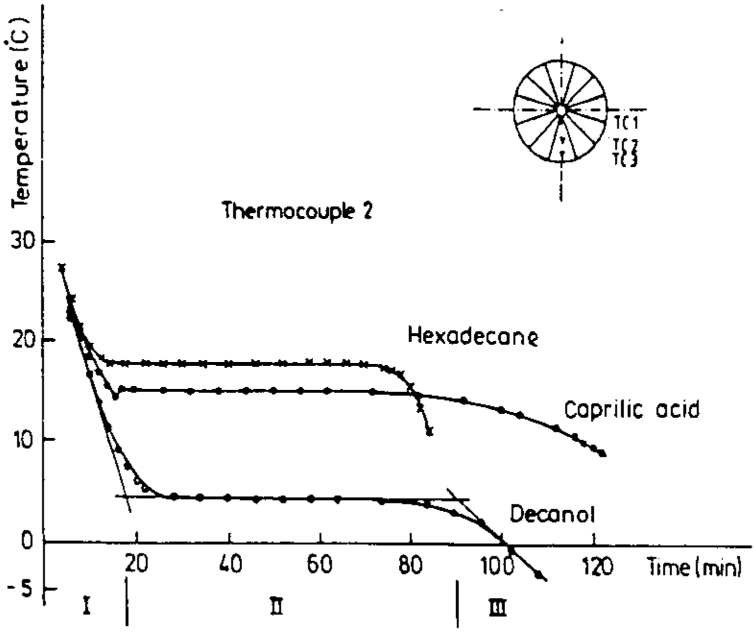


Fig. 6 Characteristic freezing curves for decanol, caprilic acid and hexadecane obtained during charging the test model using the outer tube calorimeter

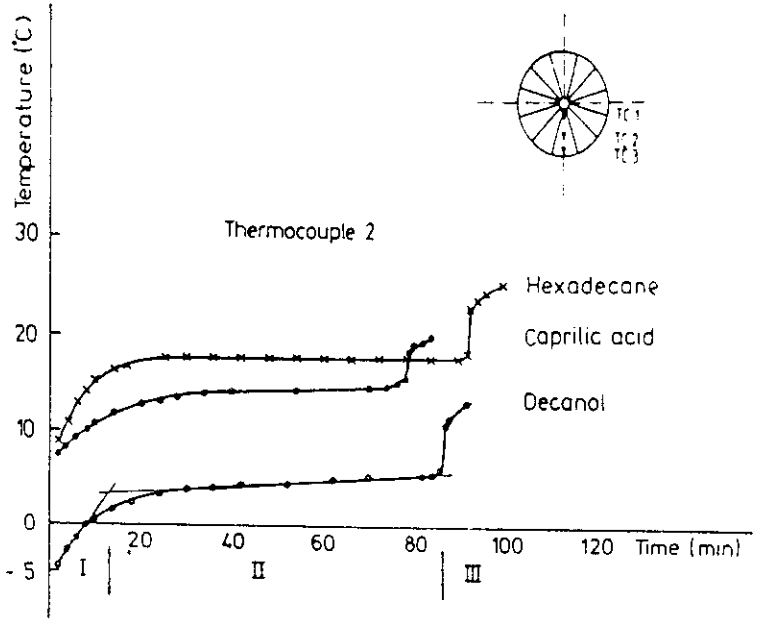


Fig 7 Characteristic melting curves for decanol, caprilic acid and hexadecane obtained during discharging the test model using the inner tube calorimeter

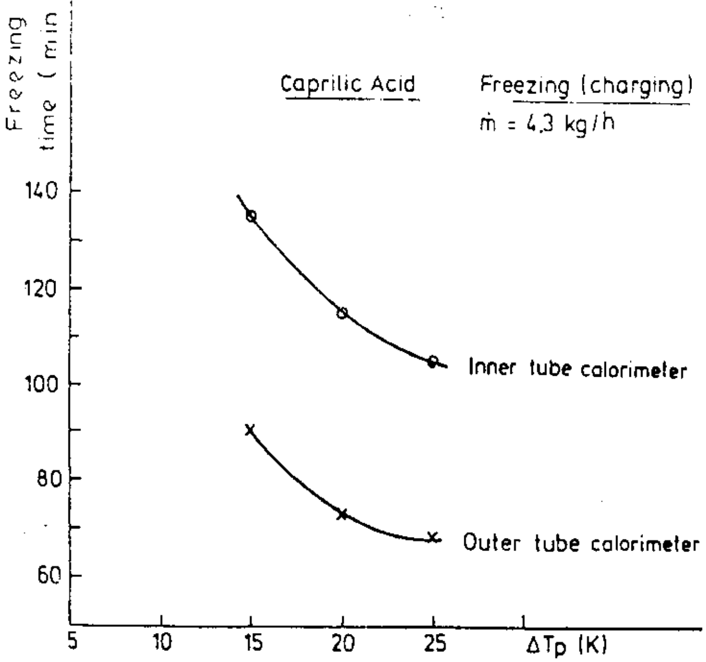


Fig. 8 Effect of ΔTp on the freezing time of caprilic acid at constant $\dot{m}$ = 4.3 kg/h using the inner tube and outer tube calorimeters

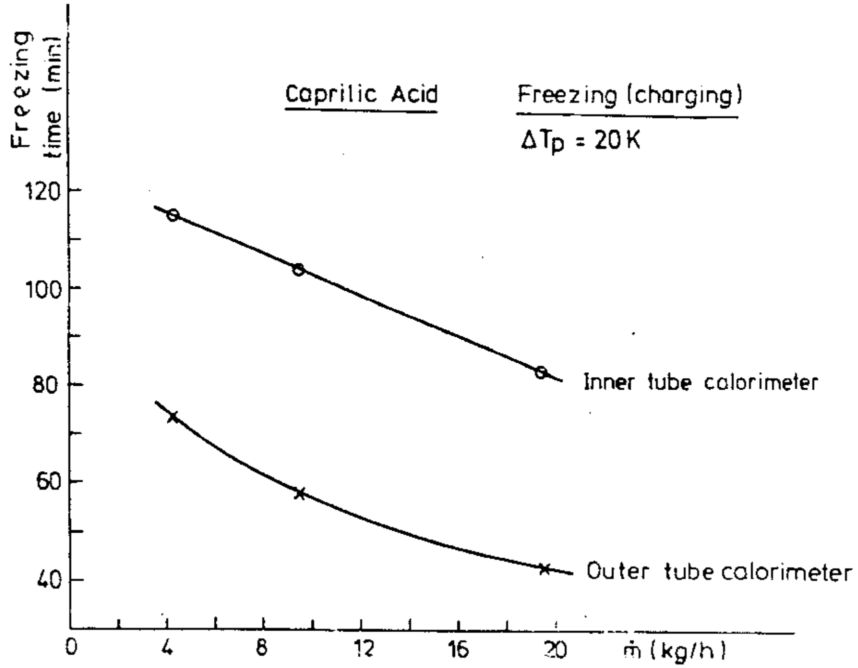


Fig. 9 Effect of mass flow rate ṁ on the freezing time of caprilic acid at constant ΔTp = 20 K using the inner tube and outer tube calorimeters

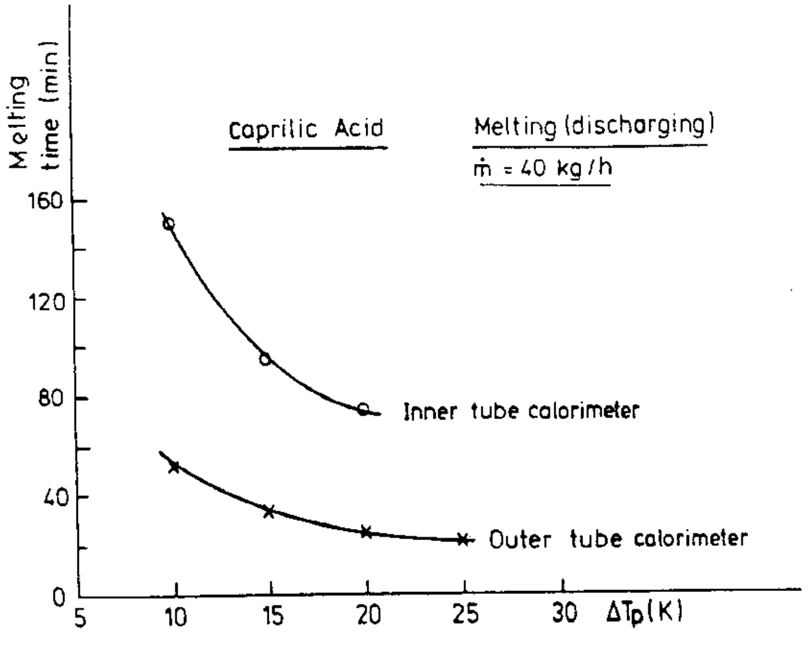


Fig. 10 Effect of ΔTp on the melting time of caprilic acid at constant ṁ = 40 kg/h using the inner tube and outer tube calorimeters

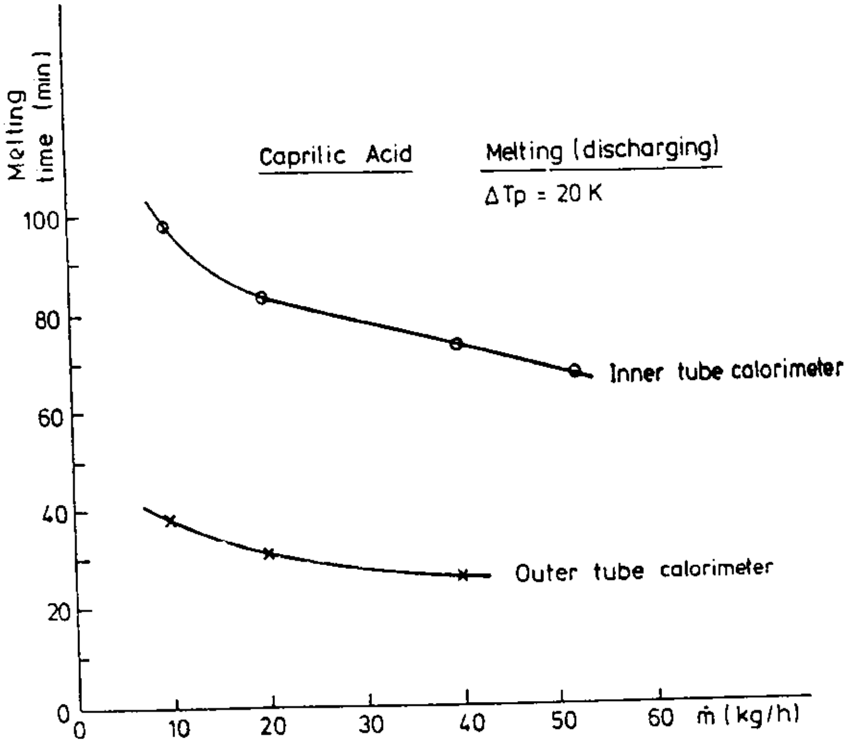
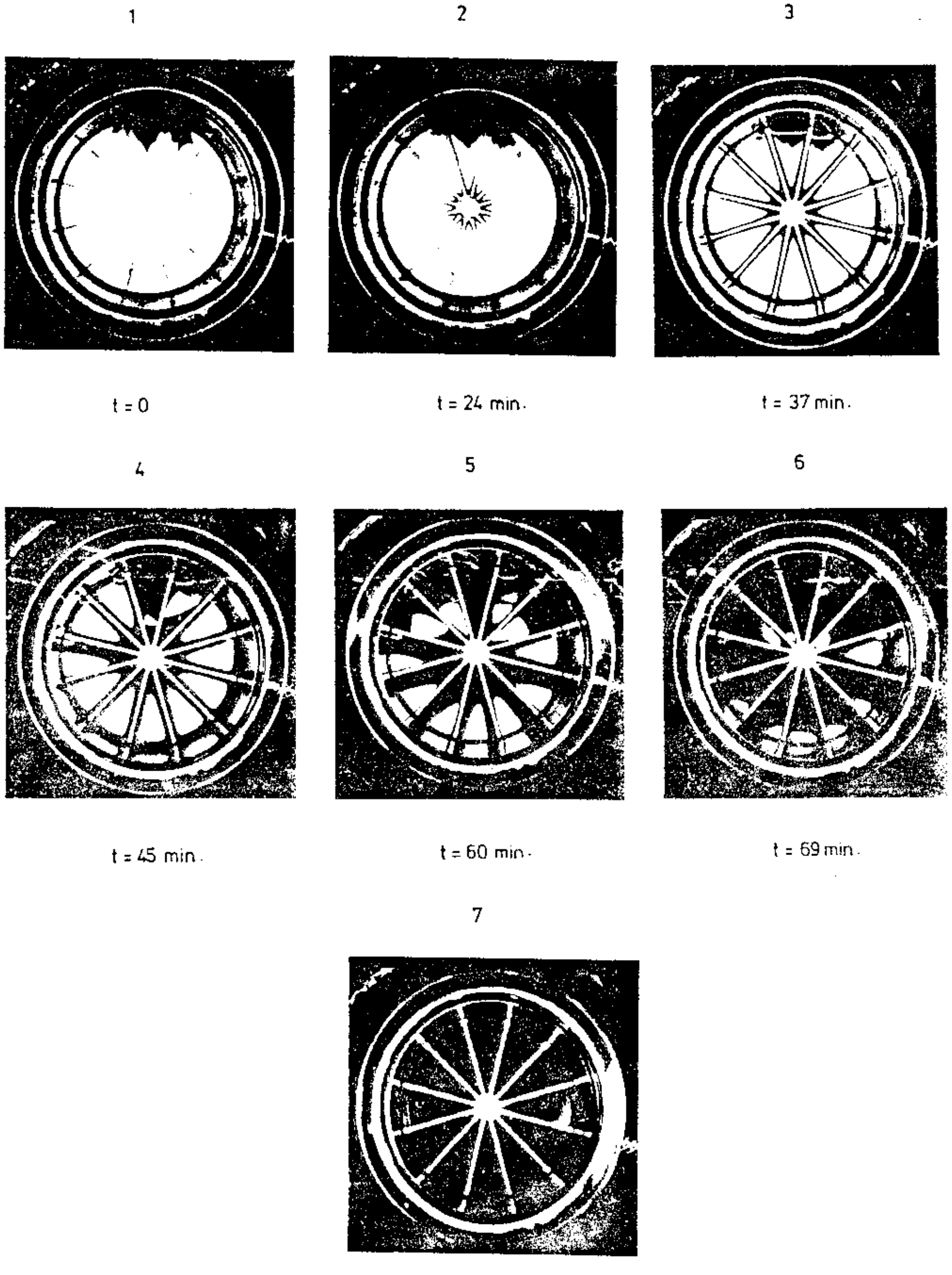


Fig. 11 Effect of mass flow rate ṁ on the melting time of caprilic acid at constant ΔTp = 20 K using the inner tube and outer tube calorimeters



1 t = 0

2 t = 24 min.

3 t = 37 min.

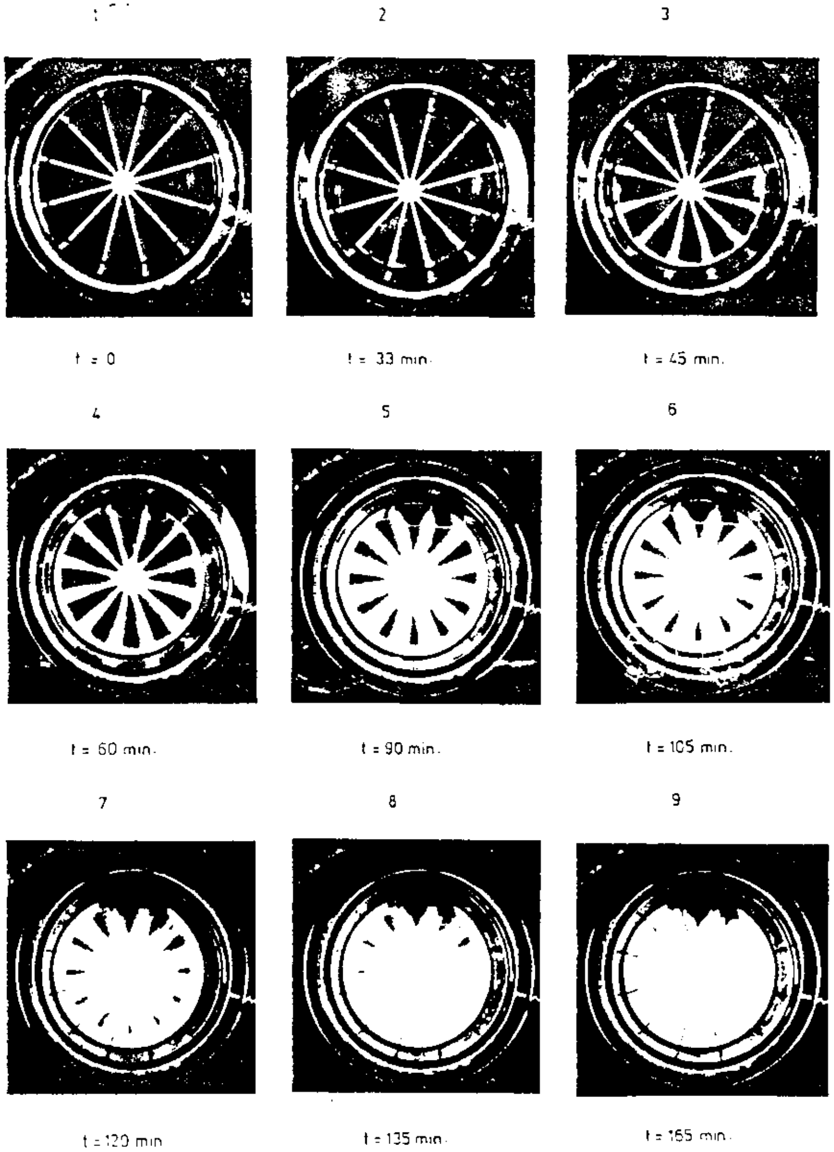
4 t = 45 min.

5 t = 60 min.

6 t = 69 min.

7 t = 81 min.

Fig. 12 Sequence of photographs during melting of decanol in the test model using the inner tube calorimeter - $|\Delta T_p|$ = 16.5 K and $\dot{m}$ = 18 Kg./h



1 t = 0

2 t = 33 min.

3 t = 45 min.

4 t = 60 min.

5 t = 90 min.

6 t = 105 min.

7 t = 120 min

8 t = 135 min.

9 t = 165 min.

Fig. 13 Sequence of photographs during freezing of decanol in the test model using the outer tube calorimeter - $|\Delta T_p| = 15$ K and $\dot{m} = 11.4$ Kg / h

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إنتقال الحراره وتحرك السطح الفاصل أثناء الإنصهار والتجمد فى الأنابيب المركزيه ذات الضلوع لأغراض التبريد

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أجريت تجارب لدراسة إنصهار وتجمد بعض المواد (أثناء تغير حالتها) والتى تستخدم فى أغراض التبريد فى المدى من صفر إلى ٢٠ م . تم إختيار ثلاث مواد لهذه القياسات وهى الديكانول وحمض الكبريليك والهكساديكان . وقد تم تصوير موضع الحد الفاصل بين الحاله الصلبه والحاله السائله أثناء تغير حالة المادة وذلك لتحديد إحداثيات هذا السطح كدالة فى الزمن كذلك تم قياس توزيع درجات الحرارة داخل هذه المواد أثناء تغير حالتها فى مناطق مختلفه من المبادل الحرارى المستخدم عند ظروف معملية مختلفة . وقد دلت القياسات على عدم حدوث Supercooling " تبريد فوق العاده " لكل من الديكانول والهكساديكان بينما سجلت نصف درجه كلفنيه Supercooling فى حالة حمض الكبريليك .

أكدت القياسات وجود تيارات الحمل أثناء الإنصهار وأنها تساعد على زيادة معدل إنتقال الحرارة بينما ساعدت الضلوع المعدنيه فى المبادل الحرارى على تقليل التأثير السلبى للحمل أثناء التجمد وأصبح إنتقال الحراره يتم بواسطة التوصيل فقط أثناء التجمد وتم حساب رقم رايلى الحرج (Ra) والذى يشير إلى تحول إنتقال الحراره أثناء التجمد عن طريق الحمل والتوصيل معا إلى إنتقال الحراره عن طريق التوصيل فقط وكانت القيم المحسوبه لرقم رايلى هى $١,٦ \times ١٠^{٧} < Ra < ٢,٥ \times ١٠^{٧}$