DETERMINATION OF THE THERMOPHYSICAL PROPRTIES OF NSUKKANUT: A SOLID ABSORBENT FOR SOLAR REFRIGERATION

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ABSTRACT

The thermophysical properties of 'Nsukkanut', - a $CaCl_2/CaSO_4$ absorbent mixture used in solid absorption solar refrigeration [1], were studied in this report. The transient experimental technique of Beck and Al-Araji [12] was used in determining the effective thermal conductivity, specific heat and bulk thermal diffusivity of granular (2.8 - 6.35 mm sizes) parkings of the absorbent. Additionally, the parking density crushing stress percentage swell and degree of refrigerant - NH_3 absorption were determined. Effective k, c and α values were in the ranges of 0.098 - 0.111 W/mk, 1.123 -1.696 kJ/kg K and 1.404 - $1.053.10^{-7}$ m^2/s, respectively, for a parking density of 621.4 kg/m^3. Average crushing stress, the percentage swell and absorption factor values 018.17 N/mm^2, 7.96% and 62.1 % respectively, obtained in this report compared well with values of 8.10 N/mm^2, 11.6% and 59.5% correspondingly, as reported in [11].

The effect of aluminium as a thermal conductivity improvement additive, on the thermophysical properties of the absorbent, were also studied. For aluminium fractions of up to 3% by mass, no sustained improvement in thermal properties were observed, while the strength and swell properties deteriorated

INTRODUCTION

The design and construction of an intermittent solid absorption solar refrigerator using the absorbent/refrigerant combination of $CaCI_2NH_3$ was presented in [1]. The absorbent, called 'Nsukkanut', was a $CaCI_2$-$CaSO_4$ mixture which was prepared in granular from, with the $CaSO_4$ acting as a stabilizing agent. Long term parametric test on the refrigerator, presented in [2] indicated that the peak available and useful coefficients of performance (COP) were respectively 0.075 and 0.53. COP's of 0.1 or more are possible for solar powered absorption refrigerators, [3, 4], and so the above performances are on the low side.

It's considered that low thermal conductivities and thermal diffusivities of the absorbent are partly responsible for the low performances of the above refrigerator, and of solid absorption refrigerators in general, [5], [6] and [7]. Scanty data exist in the literature on the thermal properties of the absorbent granules and this hampers theoretical design, analysis and prediction of performances of solid absorption refrigerators. It is thus necessary that thermal properties of the absorbent granules be determined, and that ways be found of improving them.

Some available thermophysical properties of $CaC1_2$, relevant to absorption refrigeration, are given in Table 1. The additive in [10] was supposed to be 3% aluminium powder by mass. In retrospect and for the tests reported in [10], the absence of Al-H_20 reaction at elevated temperatures which should lead to the evolution of H_2 during sample preparation, casts doubt on the nature and quality of the additive used. The k-values may thus only be considered indicative. The tests reported in this paper involve a more controlled repetition of the tests in [10]. Aluminium was chosen as a thermal conductivity improver additive because of its high k-value, while copper was rejected because it is attacked by NH_3.

For the absorbent granules, it is desirable that the crushing stress and % NH, absorbed be high, and that volumetric swell be low Thus in seeking to improve the thermal properties of Nsukkanut through use of additives, care must be taken to ensure that the above physical properties do not deteriorate, at least excessively, when compared to values for the untreated sample.

It is noted that since the absorbent samples are in packed granular from, only the effective thermophysical properties of the packings can be obtained.

Objectives or Test Programme

These can be summarized as follows:

a) To establish the proper procedure for preparing the sample granules in the presence of aluminium additives.
b) To determine the effective k, c and α values of Nsukkanut.
c) To determine the crushing stress, absorption factor and percentage swell of Nsukkanut.

Table 1: Thermal, Strength and Absorption properties of $CaCl_2$

Reference	K-W/mk	Crushing Stress N/mm^2	% NH3 Absorbed	% Volume Swell	Sample Condition
8	0.087	-	-	-	Powder
9	0.12-0.23	-	100	300-400	Powder
11	-	8.10	59.5	11.16	Nsukkanut
10	0.147-0.183	-	-	-	Nsukkanut+Additive

d) To determine the more suitable form of aluminium (powder or filings) to be used for the tests, and to repeat (b) and (c) for Nsukkanut with varying proportions of the aluminium

The determination of the thermal conductivity of a material is based on Fourier's law and on the solution of the conduction equation for the particular initial and boundary conditions, and geometry, of the material. If homogeneous and isotropic assumptions are made, the equation is given by

$$k\nabla^2 T + u = \rho v\frac{\partial T}{\partial t} \qquad (1)$$

In experiments to determine k, it is usual to arrange the geometry and boundary conditions such that one dimensional heat flow exists. The ease of maintaining one dimensional heat flow, which is determined by the number of surfaces whose conditions have to be maintained at uniform or known conditions, decreases from spherical, through cylinderical, to rectangular geometries. The cylindrical geometry is however the easiest to machine accurately and so was chosen for the present test, with an L/D > 5 so as to minimize and effects.

There are several methods, all based on the solution of equation 1, for determining material thermal properties. In contrast to methods using analytic and exact solutions of the steady state or transient problem, those based on numerical solutions of the governing equations are usually capable of yielding more than one property at a time; However, a method which uses a simple analytic solution of the equation while yielding many thermal properties at a time has been developed by Beck and Al-Araji [12], and was chosen for the present tests. It requires only that one of the two surfaces perpendicular to the heat flow direction be heated arbitrarily while the other surface is insulated 'perfectly'.

Application of the method to the cylindrical geometry yields the following equations:

The Cylinderical equation of conduction is given by

$$\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right) = \rho C\rho\frac{\partial T}{\partial t} \qquad (2)$$

The boundary and initial conditions (see figure 1)

$$-k\frac{\partial T}{\partial r}(r_i,t) = q(t) \qquad (3)$$

$$\frac{\partial T}{\partial r}(r_o{'}t) = o \qquad (4)$$

$$T(r,o) = T_{in} \qquad (5)$$

Equation 2 is first integrated with respect to time between o and ∞, and then with respect to r to obtain:

$$r\int_{o}^{\infty} k\frac{\partial T}{\partial r}dt = \frac{r^2}{2}\int_{T_{in}^{\rho}}^{T_f} C_p dT + C \qquad (5a)$$

By evaluating equation 5a at r_i and r_o' and combining it with the integration of equations 3 and 4 between t = o and ∞, the parameters C and $\int\rho C_p dT$ can be eliminated from equation 5a.

Integration of the resulting equation with respect to r, between r_i and r_o will yield the result:

$$\frac{k = r_iQ(0.5-(1nr_o/r_i)/(1-(r_i/r_o)^2)}{\int_{o}^{\infty}(T(r_o,t)-T(r_i,t))dt} \qquad (6)$$

Irrespective of the dependence of ρ and C_p on T.

If ρ and C_p are assumed constant, then

$$\rho Cp = \frac{2r_iQ}{(r_o{}^2-r_i{}^2)(T_f-T_{in})} \qquad (7)$$

$$\propto = \frac{k}{\rho Cp} =. \frac{5(0.5(r_o{}^2-r_i{}^2)-r_o{}^2 1n\, r_o/r_i\,(T_f-T_{in})}{\int_o^\infty (T(r_o,t)-T(r_i,t))dt} \qquad (8)$$

If k and ρ are constant and $C_p = C_p(T)$ then the mean values of C_p and α over the temperature range T_{in} to T_f, are still given by equations 7 and 8.

Thus if $Q, \int_o^{t\,max}(T(r_o,t)-T(r_i,t))dt$ -(where $(T(r_o,t) \approx (r_i,t)$ for t > t_{max}) T_{in}, T_f, r_i and r_o are known, then " C_p an α can be determined from a single experiment.

The effective thermal conductivity of a packing of spherical granules of a material is given by the Maxwell-Euttcn equation, (13),

$$k_{eff} = k_c\frac{(1+2B(1-k_c/k_d)/(2k_c/k_d+1))}{(1-B(1-k_c/k_d)/(1+\frac{k_c}{k_d}))} \qquad (9)$$

where B_s = volumetric fraction of the discontinuous phase. Also, by using the method of resistances, the k_{eff} of a simple, parallel packing of equal rectangular solid slabs separated by another medium, for series' heat flow through the slabs, can be shown to be given by

$$k_{eff} = \frac{k_s\ k_m}{B_s\ k_m + (1-B_s)k_s} \qquad (10)$$

where B_s = volumetric fraction of the slab; k_s k_m = thermal conductivities of slab and medium , respectively. Equations 9 and 10 are valid, irrespective of the order in which the heat flow vector encounters the materials. Thus, we may expect that the values of k_{eff} obtained in our experiment for any particular packing of the granules, will be valid for any other packing provided the volumetric fraction is the same. If the density of the absorbent granules is constant, the same conclusions are valid for specific heat. The situation is different with α_{eff} Schimel et al have shown in [14] that the effective α is strongly dependent on the order of the arrangement of the constituents of the mixture, with respect to the heat flow vector. Thus experimental values obtained using equation 8 will only be valid for the particular arrangement of granules in the text. This fact imposes a difficulty in interpreting and using the results for α_{eff} since the order cannot be predicted in advance.

EXPERIMENTAL PROGRAMME

Sample preparation Procedure

The method developed in [11] for preparing Nsukkanut was applied, in the presence of the aluminium additive. The mixture of C_aCl_2, $CaSO_4$. and Aluminium was found to foam excessively upon beating and to produce a – very porous and weak structure after oven drying.

This behavior was attributed to the reaction between aluminium and water at elevated temperatures. The reaction causes the evolution of flammable gases, chiefly hydrogen [l5], while oxidizing to Al_2O_3,according to the equation;

$$Al_2 3H_2O \rightarrow Al_2O_3 + 3Hz \qquad (11)$$

The properties of anhydrous and hydrated $CaCl_2$and $CaS0_4$, as well as of Aluminium, were further studied, and a number of' pilot tests were carried out in order to find out the appropriate procedure, particularly the beating programme, for producing hard and reasonably porous granules. The results of the studies and tests are detailed in[16]. In particular it was found that the Al-H_2O reaction was significant at 60 °C and above, and that aluminium powder gave a more porous but weaker structure than aluminium filings of the same mass ratio. Consequently, the latter was used. The preparation procedure adopted is described below.

The $CaCl_2$ pellets were oven heated at 120 ^{o} C, the ground to powder, and repeatedly weighed while heating at 120°C until no further reduction in weight occurred. Masses of the $CaCl_2$, $CaS0_4.1/2\ H_2O$ powder and aluminium, to give the required mass ratios (see Table 2) were weighed out and mixed with distilled water to a thick paste. The respective masses allowed for the actual $CaCl_2$ (79%) and $CaS0_4$ (93.8%) contents of the source materials. The paste was heated, in a 250 x 100 x 50 mm mild steel tray, in an oven at 50°C for 2 hours, followed by two-hour heating at subsequent temperature levels, at 10 °C step increases up to 190 ^{o} C, then at 200 °C for 12 hours and 250^{o}C for 6 hours. The above heating procedure was adopted from an analysis of the hardness, consistency and porosity of samples obtained from seven pilot tests, using different procedures [16]. The hard porous mix was then crushed, and using two sieves of mesh sizes 2.8 mm and 6.35 mm, granules in the size range 2.8 - 6.35 mm were obtained. Most granules were closer to 6.35 mm.

For the crushing strength tests, flat rectangular pellets of size range, 8 x 9 mm to 12 x 17mm and 3 - 6 mm thick were prepared using a sharp knife. The test granules and pellets were further heated at 250. °C for 1 hour and 300 °C for 1 hour to remove moisture accumulated during processing, and stored in a desiccator when not in use.

Apparatus and Procedure for absorption and Swell Tests

The assembly of the absorption and regeneration test apparatus is as shown in figure 2. The detailed description is given in [17]. The 131 mm i.d x 140 mm o.d x 450 mm high pressure vessel is fitted with NH_3 supply and vent lines, and has co-axial wire mesh tube of diameter 85 mm. The sample granules are located in the annular space thus created. The vessel sits in a tank containing stagnant water for removal of the heat of absorption. The assembly also has NH_3 supply tank, water trap and water bucket for reducing NH_3 effluents.

For the tests, the pressure vessel and internal were weighed with and without the, granules, with a Gallenkamp balance of reading error ± *25* gm. The

Sample No.	$CaCl_2$:$CaSO_4$:A1	Form of A1
1	80: 20: 0	- - -
2	79: 20: 1	Fillings
3	78: 20: 2	Fillings
4	77: 20: 3	Fillings
5+	80: 20: 0	- - -
6	79: 20: 1	**Al – Bronze Powder**

+ Specimen 5 was heated from 95 - 200^0C

granule depth in the anulus was determined with a dip stick and meter rule, as the average of readings at four locations 90^0 circumferentially displaced. After assembling the system, the NH_3 valve was adjusted such that NH_3 bubbles issued at a slow but steady rate into the water bucket. At the end of absorption the vessel was reweighed and the granule depth re-measured.

Apparatus and Procedure for Crushing Stress Tests

A Hounsfield Tensometer, model No. 8889 was used to determine the crushing load. The loading beam capacities used were 250 g and 500 g. The flat specimen pellets were held between the jaws of the tensometer as the load was applied. A sudden jerk in the mercury movement in its capillary tube indicated the cracking of the specimen. A load displacement plot also assisted in determining specimen cracking. Ten pellets from each sample preparation, five from each of the top and bottom layers, were tested. The arithmetic mean gave the crushing stress for the sample.

Apparatus and Procedure for Thermal property Tests

The apparatus, which is a modified form of that built by S. Abisuga and S. Enibe (18), is as sketched in figure 3., The heater wire was wound in helical groves on a tubular plastic core called the heater coil bolder. The tubular assembly was insulated with a tight packing of glasswool within a wooden box. Three copper constantan thermocouples were, for convenience, located on the outside surface of the specimen holder, instead of on its inside surface, and at 76:5 mm axial intervals from the bottom, Three other thermocouples were similarly attached to the outside surface of the beater former.

Power supply was through a variac and a 0-10A ammeter With a reading error of ± 0.1A The heating time was measured with a stop watch of reading error ± 0.01 Sec. Thermocouple traces were recorded on a multi-pen Yokogawa Electric chart recorder, Type 3061 with an accuracy of ± 0.25% full scale. The thermocouples whose output were used for data reduction were the inside middle I_m, and outside middle 0_m ones, and the potentiometer inputs were connected such as to give traces of I_m, Om and Im – Om. Other thermocouples were for purposes of comparison and checks for one-dimensional radial heat flow.

A known mass of granules was packed into the annular space provided, while taping the specimen holder to increase packing density. The gaps at test assembly joints were sealed with volvo wind screen sealant, and araldite. With variac pre-set to give a current of 2A, the stop watch and power were simultaneously switched and then off when beater former temperature risen to about 60 °C. Trace data were congaing, recorded until 1m - Om read approximately. The assembly was allowed to cool to ambient temperature, after which the experiment repeated. Three sets of readings were obtained for each specimen.

RESULTS AND DISCUSSIONS

Data Reduction

Typical temperature traces are shown in figure 4. From these T_{in}, T_f and (T_{r2} -;T_{ri}) vs time can be read. Thermocouple calibration gave the relationship

T = 235. (mV) (12)

The initial and final granule temperatures averages of all the thermocouple readings.

$$\int_{o}^{\infty} (T_{r2} - T_{ri})dt \approx \int_{o}^{t_{max}} (T_{r2} - T_{ri})dt = A * I_{v**fr*ft} \qquad (13)$$

Where A = Area under the (1_m - O_m) trace,

(cm^2) using Simpsons rule

f_V = Voltage scale factor on potentiometer . (mV/cm)

f_r = Thermocouple transducer coefficient = 23.5*C/mV

f_t = Time scale factor on potentiometer chart drive (s/cm = reciprocal of chart speed)

Heat supplied per unit of sample inside surface area is given by

$Q = (Q' - Q_{loss})/2\pi r_i L$ (14)

Where

$Q' = I^2 R t_h$

Q_{loss} = Heat gain by heater former and heater coil holder. Heat gain by heater coil and end retainers were found to be negligible.

Since the outside surface temperature of the specimen holder was measured instead of that of the specimen, the k_{eff} calculated using equation 13 in the denominator of equation 6 would be that of the specimen and specimen holder combined. Using a steady state thermal resistance model to correct for this effect, the k_{eff} for the specimen alone becomes

$$k_{eff} = \frac{k^*_{eff} 1n\, r_o/r_i}{1n r_2/r_i - (k^*_{eff}/k_s) 1n\, r_o} \qquad 15$$

Also since the heat flow into the specimen through the inside surface area increased the sensible internal energy of both the specimen and the specimen holder, the corrected specific heat of the sample would be given by

$$C_{ff} = \frac{Q}{m_g T_f T_{in}} - \frac{m_s C_s}{m_g} \qquad (16)$$

The effective thermal diffusivity is calculated using the equation

$$\propto_{eff} = k_{eff}/\rho_{eff} C_{eff} \qquad (17)$$

Where ρ_{eff} = granule mass/specimen volume (18)

The percentage NH_3 absorbed, X, percentage swell, Y and other absorption and strength properties are calculated with the following definitions

$$X = \frac{Mass\ of\ NH_3\ absorbed * 100}{Maximum\ mass\ of\ NH_3\ that\ can\ theortically} \qquad (19)$$

$= m_a * 100^2/ (S.X.mg)$ % (20)

$$Y = \frac{Increase\ in\ sample\ height\ aftere\ absorption * 100\%}{Sample\ Height\ before\ absorption} \qquad (21)$$

$$r = \frac{1}{N}\sum_1^N \tau_j \quad (N = 10) \qquad (22)$$

$$f = \eta * crushing\ stress * \%CaC1_2 in\ sample/100 \qquad (23)$$

$$= \eta * \tau \frac{Z}{100} N/mm^2 \qquad (24)$$

From Table - 3 below and reference (11), a value of η = 0.6 was used:

$\$ = \eta\tau Z k_{eff}/100 = f * k_{eff}\ N^2/mm^2/ sK$ (25)

$\phi = \eta\tau Z k_{eff}/100 = f * \alpha_{eff}\ N/s$ (26)

Factors f, S and Ø contain the various physical and thermal properties determined. They are thus considered to be capable of giving better overall indications of the combined thermophysical quality of the sample than the individual variables which define the factors. Table 3 below gives a summary of all the properties of the samples as determined in the experiments.

Analysis of Results

From figure 4, it is seen that inside surface temperatures role rapidly with the start of heating, and fell approximately to the same asymptotic values which the outside surface temperatures rose to with the removal of heating. Heating time varied from 89.8 to 148.23 seconds. The outside surface thermocouples showed negligible differences. As argued in[16], the differences observed for the inside surface thermocouples were probably due more to signal processing differences in the transducer channels than to real differences in temperatures.

Repeatability tests for the thermal properties were generally satisfactory. For sample - 1, with ρ_{eff} of 621,4 kg/m^3, 0.098 < k_{eff} ≤ 0.111 W/mK; 1·123 ≤ C_{eff} ≤ 1.696 kJ/kgK; and 1.404.-10^{-7} ≤ α_{eff} ≤ 1.053 - 10^{-7} m^2/s. The average values are plotted in figures 5 to 7

The k_{eff} did not show a definite trend with %, aluminium.

The values were expected to increase with increasing aluminium content. However increasing Aluminium Content resulted in increasing porosity, due to the aluminium-water reaction and this in turn decreased the thermal conductivity. Thus the

Table 3 - Summary of Thermophysical Properties of the Specimen

Sample	compostion	ρ_{eff} kg/m3	k_{eff} W/mk	C_{eff} kJ/lgK	α_{eff}* $10^7 m^2/s$	X %	Y %	τ N/mm^2	F N/mm^2	$ N/mm^2 sk	Q N/s
1	80:20: 0	621.4	0.105	1.478	1.174	62.1	7.96	8.17	4.06	0.43	0.48
2	79:20:1	512.8	0.078	1.175	1.355	60.1	6.72	7.98	3.79	0.30	0.51
3	78:20:2	569.8	0.102	1.261	1.526	(60.0)	8.40	4.58	(2.14)	(0.22)	(.033)
4	77:20:3	470.3	0.086	1.943	0.955	(60.0)	12.69	3.11	(1.44)	(1.44)	(0.14)
5	80:20:0	661.3	0.099	1.752	1.190	-	-	-	-	-	-
6	79:20:1	535.5	0.078	1.094	1.347	-	-	4.38	-	-	-

+ composition = $CaC1_2$: $CaSO_4$: Aluminium

See also Table – 2 for more details
() Values using estimated absorption factor of 0 : 6

increased porosity would tend to neutralize whatever increases resulted from increased aluminium content. Figure 5 also shows the plot ofρ_{eff} vs % aluminium.

The trends shown byρ_{eff} are similar to those shown by ρ_{eff}. Increasing ρ_{eff} is associated with decreasing porosity and hence higher K_{eff} Figure 6 shows a plot of k_{eff} and ρ_{eff}. A least square linear fit to the data gave

$$k_{eff} / 10^{-4} = 2.63 + 1.62\, \rho_{eff} \qquad (27)$$

$$\text{or } k_{eff} \approx 1.62.10^{-4}\, \rho_{eff} \qquad (28)$$

Because of the few data points used in the curve fit, equations 27 and 28 should be used with care, and preferable within the range $470 < \rho_{eff} \leq 661$ kg/m^3 in which the data points fell with a correlation coefficient of 73%. With this direct correlation of ρ_{eff} with parking density, the influence of % aluminium was felt more through its effect on packing density, than through its intrinsic thermal conductivity. From Table 3, k_{eff} is seen to vary over 0.078 - 0.105 W*/mK.* These compare well With the value quoted in [16] and are on the lower end of the values in [7], for powdered $CaC1_2$, as shown in Table - 1.

Figure 7 indicates that C_{eff} goes through a minimum value, between 1% - 2% aluminium, as % aluminium increases. The average value for all the tests is 1.451 kJlkgK. At 0% aluminium content, the experimental value of 1.48 kJ/kgK may be used for design calculations, at the given packing density.

The plot for ρ_{eff} is also shown on Figure 7 There is an apparent linear increase of ρ_{eff} with%· aluminium between 0% and 2%, followed by a sharp drop at 3%alliminiuin. The value of *1.18-10-*^{7} *m*^{2}*/s* is recommended at 0% aluminium and ρ_{eff} of 621.4 kg/m .

Table 3 indicates experimental values of percentage NH_3 absorbed at 0% and 1% aluminium contents to be 62.1% and 6o.1% respectivly. These agreed very well with the value of 59.5% obtained for non-aluminized Nsukanut in [11]. arid shown in Table 1. The values obtained for' 2% and 3% aluminium were lower, and unreliable. It is argued that a decrease in % NH_3 - absorption is not compatible with the increased porosity and easier migration of NH_3 within the granules, which results with increased aluminium content. It is likely that an extrapolated value of 60%, based on the consistency of the results quoted above would be valid for the samples with 2% and 3% aluminium contents.

Fagure 8 indicates a tendency of the % swell to increase as % aluminium increases. The values of 8% and 12.7% swell for 0% and 3% aluminium respectively may be compared to 11.6% swell obtained in [11] for non-aluminized Nsukkanut as shown in Table 1. The tendency for' % swell to increase with increasing aluminium content may be due to the reduced bonding strength shown in figure 9.

In figure 9, the crushing stress and the strength capacity factor, are shown to change very little at 0% and 1% aluminium contents, but to drop drastically for higher %, aluminium The crushing stress is a measure of the bonding strength of the Nsukkanut. It would seem that the increased porosity at higher aluminium contents decreased the bonding strengths drastically, and consequently, the strength -capacity factor. It is interesting to note the agreement between the value for crushing stress of 8.17 N/mm^2 for 0% aluminium obtained in these tests. With the value of 8.10 N/mm^2 in ported in [11] and shown in Table 1.

The strength-capacity-conductivity and strength-capacity-diffusivity factors, S and ϕ, are measures of the combined thermophysical qualities of the granules. Both factors plotted in figure 9, indicate decreasing trends with % aluminium, except for ϕ which showed a slight increase between 0% and 1% aluminium before decreasing.

The combined properties are therefore not improved with the addition of aluminium.

CONCLUSION

1. The addition of aluminium to the Nsukkanut increases the porosity of the granules, as a result of the aluminium-water reaction during heating.
2. Prom strength considerations, it is better to use aluminium filings as opposed the powder, since the latter produces more vigorous reactions and porosity.
3. The values of effective thermal conductivity varies over 0.078 – 0.105 W/mK, with an average of·0.091 w/mk, and did not show any specific trend with % aluminium. These values compare wc11 with ·that quoted in [8] for powdered $CaC1_2$, - ie. 0.087 W/mK
4. The effective thermal conductivity was more dearly dependent on the packing density. A least square linear curve - fit of the data; of the form $k_{eff} \approx 1.62 \times 10^{-4} \rho_{eff}$, was obtained with a correlation coefficient of 73%.
5. The values of effective specific heat appear to have a minimum between 1 % and 2% aluminium. A value of 1.48 kJ/kgK is recommended for non-aluminized Nsukkanut, at $\rho_{eff} = 621.4$ kg/m^3
6. The effective thermal diffusivity initially increased linearly with % aluminium, up to 2% aluminium, after which it dropped drastically to 0.96 m^2/s at 3% aluminium content. A value of 1.18 x $10{-}^{7'}m^2/s$ is recommended ·for non-aluminized Nsukkanut at 621.4 $kglm^3$ packing density. This should be considered a representative, estimate because of the order effect on this property.
7. Percentage swell increases slightly with the addition of aluminium.
8. The addition of aluminium reduces the bonding strength of Nsukkanut, as well as its combined absorption and strength quality.
9. The combined thermo-physical qualities of the strength-capacity diffusivity factors both deteriorate with increasing aluminium content.
10. Prom consideration of the relevant thermo-physical properties of the aluminized Nsukkanut, no advantage could be observed from the addition of aluminium.

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NOMENCLATURE

C, C_p	Specific beat at constant pressure	kJ/kgk
D	Diameter	m
F	Strength-capacity factor	N/mm^2
I	Current	A
K	Thermal conductivity	W/mk
L	Axial length	m
M	Mass	kg
mV	Millivolt	mV
N	Number of granule samples for crushing strength test	
Q	Heat addition per unit area	J/m^2

q	Heat flux	W/m^2
R	Electrical resistance	Ω
r	Radius	m
S	Maximum kg-NH_3/kg-$CaC1_2$ that can be absorbed	
t_{max}	Test time	sec
th	Heating time	sec
u	Heat generation rate per unit volume	w/m^3
X	% NH_3 absorbed	%
Y	% swell	%
Z	% $CaC1_2$	%
α	Thermal diffusivity	m^2/s
ρ	Density	kg/mm^2
τ	Crushing stress	N/mm^2
η	Maximum fraction of NH_3 absorbed	
\$	Strength –capacity-conductivity	factor N^2/mm^2sk
ϕ	Strength –capacity-diffusivity factor	N/s

SUBSCRIPTS

a	ammonis
c	continuous
d	discontinuous
eff	effective
g	test granules
i	specimen inside surface
o	specimen outside surface
2	specimen holder outside surface
In	initial
f	final
ri	heater former outside radius
r2	specimen holder outside radius
s	steel
x	x-direction

REFERENCES

1. O.C. Iloeje, Design, Construction and Test Run of a Solar Powered Solid Absorption Refrigerator. *Solar Energy* Vol. 35. No.5, pp 447 - 455 (1985).

2. D.C. Iloeje, Parametric Effects on the Performance of a Solar Powered Solid Absorption Refrigerator. Proc. of 9th Biennial Conference of Int. Solar Energy Society, INTERSOL 85, Montreal, Canada, Vol. 2 pp 736 - 743, (1985).

3. P, Worse – Schmidt, Solar Refrigeration for developing Countries Using a Solid Absorbing Cycle, *Int. J. of Ambient Energy*, Vol. 4, No.3, (1983)

4. M. Pons and Ph. Grenier, Solar Ice maker Working with Activated Carbon-Methhanol Absorbent-Adsorbate Pair, Proc. 9th Biennial Conference of Int. Sol. Energy Soc., INTERSDL 85, Vol.2, PP 731- 735, Montreal Canada (1985).
5. O.C. Iloeje, Improvements to the /Design of a Solid Absorption Solar Refrigerator. Technical Report No. SE-5, Solar Energy Project, Univ. of Nigeria, Nsukka (Sept. 1986).

6. Rodolph De Hartoulari and Louis - Claude Dufour, Affinity Thermal Machines and Metallic Salt-Ammonia-Ammoniate Systems. *Solar Energy* Vol. 33, No.6, pp 479 - 483 (1984).

7. C.C.O. Ezeilo, On the Thermodynamics of Solar Assisted Air-Conditioning in Hot Humid Climates using the Intermittent Ice Maker. NJET Vol. 5, No.1, (1982).

8. RM. Buffington, Absorption Refrigeration with Solid Absorbents. *Refrigeration Engineering*, p. 138 (Sept. 1933)

9. P.B. Nielson and P. Worsoe-Schmidt, Development of Solar Powered Solid Absorption Refrigeration System, Part 1: Experimental Investigation on the Generation and Absorption Processes. Report No. F30 - 77. The Technical University of Denmark, Refrigeration

Laboratory (Aug. 1977).

10. T.O. Okeke, Improvement of the Thermal Conductivity of Nsukkanut: An Absorber-Generator Material for Solar. Powered Refrigerator. B. Eng, Thesis, Dept. of Mech. Eng., University of Nigeria, Nsukka (June 1986).

10. O.C. Iloeje, Quantitative Comparisons of Treated $CaC1_2$ absorbent for Solar Refrigeration. *Solar Energy*, Vol. 37, No. 4, pp 253 - 260 (1986).

12. J.V. Beck and S. Al-Araji Investigation of a New Simple Transient Method of Thermal Property Measurement, *ASME J. of Ht. Tr., Transactions* pp 59 - 64 (Feb 1974).

13. W.O. Kingrey, Introduction to Ceramics, John Wiley and Sons Inc., N.Y., P. 501.

14 P. Schimmel Jr., J.V. Beck and A.B. Donaldson, Effective Thermal Diffusivity for a Multlayer Composite Laminate, *ASMB J. of Ht. Tr., Transactions*, Vol. 99, pp. 466 – 470 (Aug. 1977).

15. J.U. Oguakwa, personal Communications, Department of Pure and Industrial Chemistry, University of Nigeria, Nsukka (1987).

16. O.C. Iloeje, Effects of Aluininium Additives on the Thermal and Strength Properties of Nsukkanut. Report No. SE-6. Solar Energy, Project. University of Nigeria; Nsukka (September 1987).

17. O.C. Iloeje, Treatments, of Calcium Chloride for use as a solid absorber in a Solar powered Refrigerator, Technical Report No. SE - 1, Solar Energy Project, University of Nigeria, Nsukka (1982).

18. S.G. Abisuga, Improvements to the Thermal Conductivity of 'Nsukkanut' An Absorber/Generator material in Solar Powered Refrigerator, B.Eng. Project, Department of Mechanical. Engineering, University of Nigeria, Nsukka.

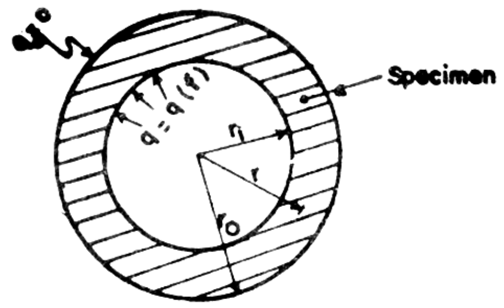


Fig. 1: Theoretical Model Geometry

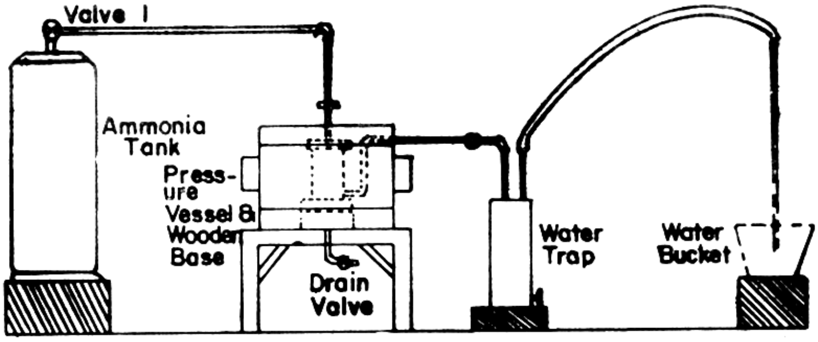
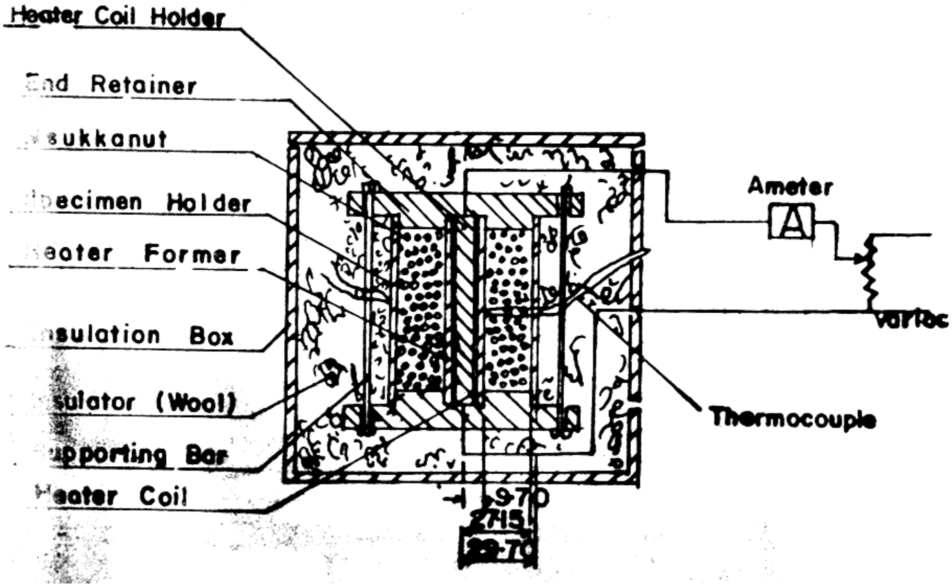


Fig. 2: Absorption Test Apparatus



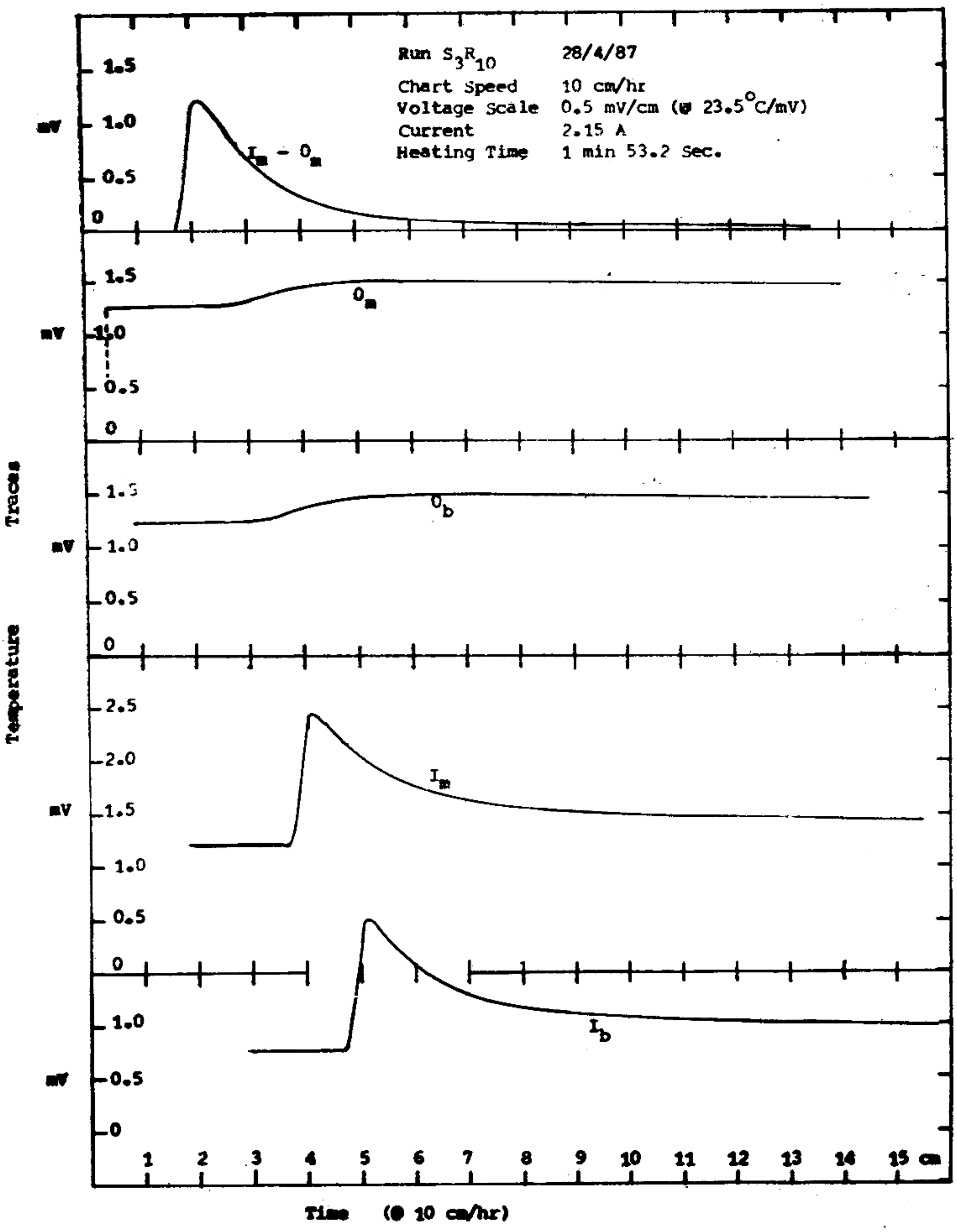
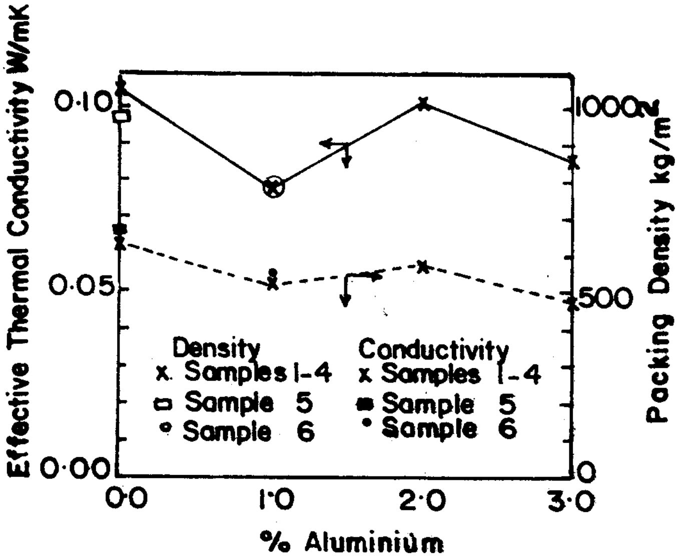
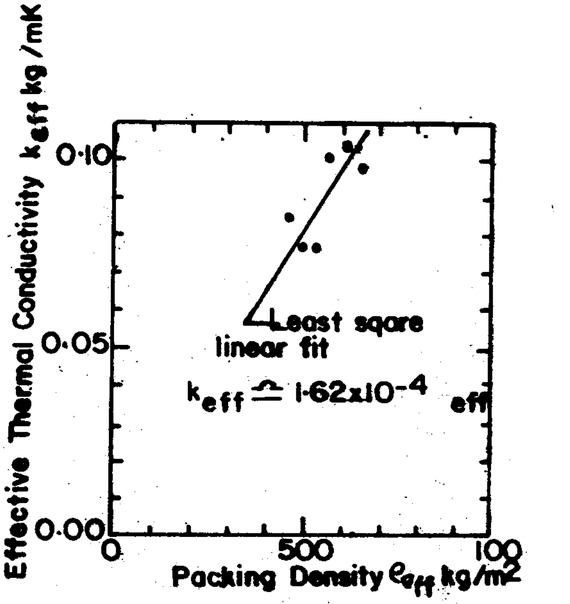


FIG. 4. Temperature Traces for Sample 3, Run 10 (S_3R_{10})



Fig· 5: Effective Thermal Conductivity and Packing Density vs % Aluminium



Fig· 6: Effective Thermal Conductivity vs Packing Density

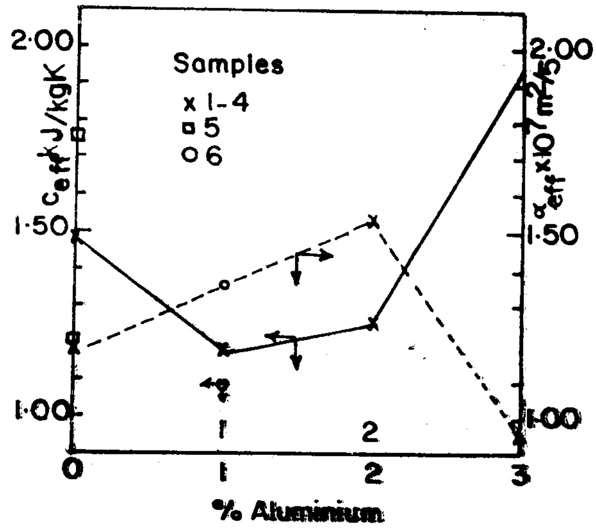


Fig. 7: Effective Specific Heat and Thermal Diffusivity vs Aluminium

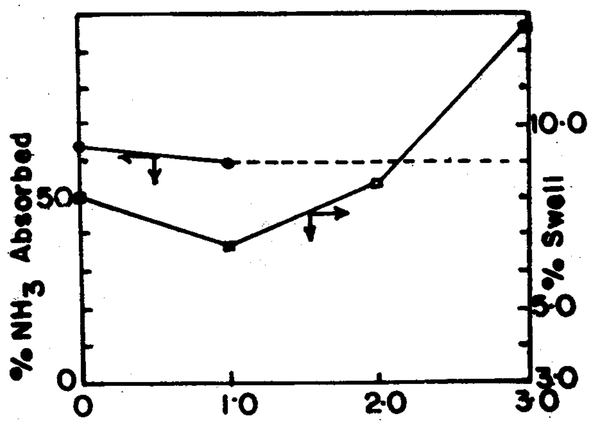
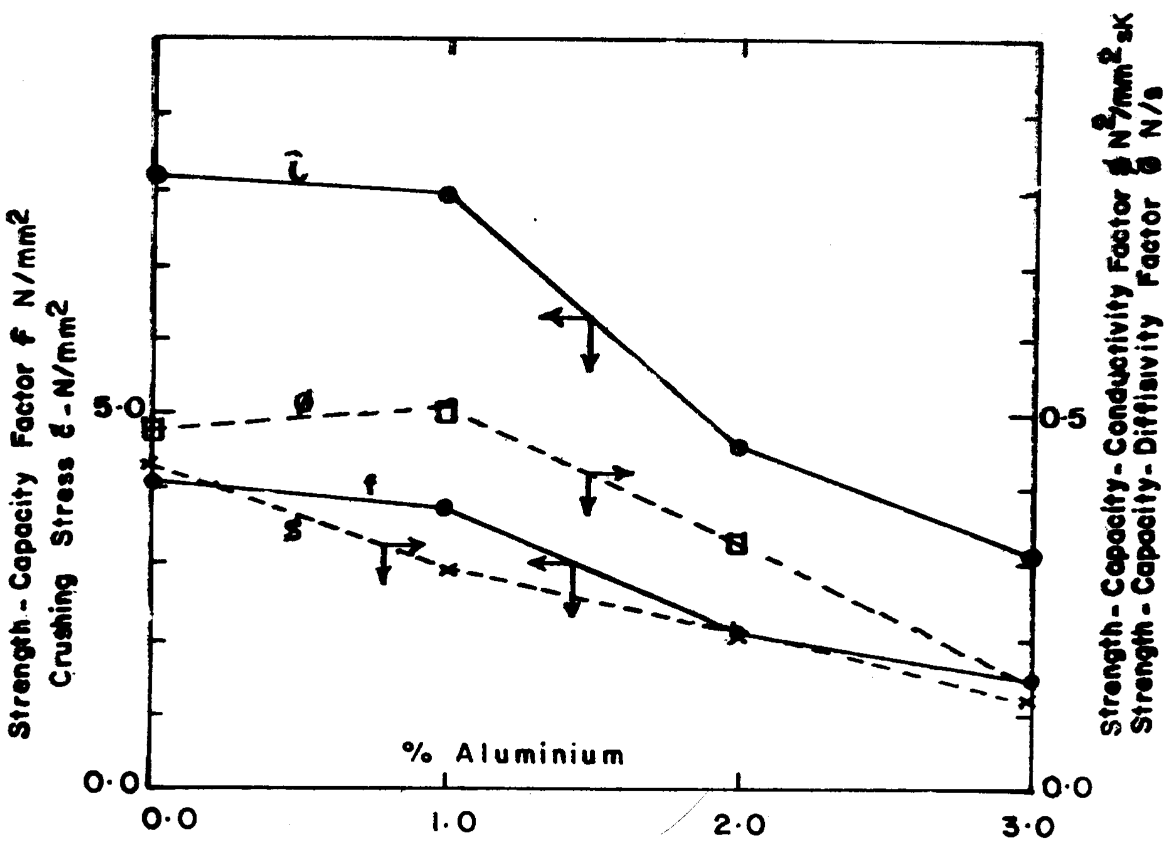


Fig 8: Absorption and Swell vs % Aluminium



Fig· 9 : Strength and Combined Thermophysical Properties vs % Aluminium