INTRODUCTION:

Heating and Cooling of food materials is an important transport process, in food industries. In the absence of any mixing device, the mechanism of heat transfer is free convection where density differences result in fluid movement. Several of the food materials such as fruit juices, products of tomato and various forms of milk products available in the market exhibit non-Newtonian rheology[2,4]. The free convection in Newtonian fluid on Cylinders, plates and noncircular tubes are extensively studied and heat transfer coefficients for steady state heat transfer can be accurately calculated[5].

Cooling and Heating of a liquid suspension in a metal container represents the case of unsteady heat transfer . In case of food products the rheology complicates predictions of heating or cooling times. In correlating the heat transfer coefficients even for steady state conditions of free convection on vertical plates or cylinders[1]. Grashoff and Prandtl numbers are to be modified for example the modified Grashoff and Prandtl numbers for a power law fluid include the rheological parameters k and n. These parameters may vary locally in food liquids in the container. In the present work condensed milk was used in stainless steel containers to study the heat transfer coefficients.

EXPERIMENTAL DETAILS:

Condensed milk was taken in a steel container of diameter = 8.1cm and height = 9.1 cm. The container is insulated both at bottom and top with acrylic sheets of thickness 1.5cm so as to ensure that heat transfer is only in radial direction. Holes were drilled in the acrylic sheets to accommodate temperature measuring sensors. PT-100 sensors were inserted through the acrylic sheet so that temperature could be measured at 5 different radial positions at an axial plane which was the middle of the contained liquid food (Fig.1). Heating and Cooling medium was water placed in a well insulated isothermal bath (±1°K).

The experiments consists of maintaining uniform initial temperature of liquid and suddenly immersing in the water bath of known temperature. The temperature at 5 radial locations were taken by a digital temperature indicator. The readings were taken until the temperature difference between the center and wall is ~ 0.5°K.

The original market product was designated as 100% condensed milk and dilutions were made with water to result in volumetric compositions of 90%, 80% and 50%. Experiments were also done with pure water in order to compare the heat transfer characteristics of Newtonian and non-Newtonian fluid. The range of variables studied are as follows:

Volumetric Compositions : 100% - 50%

Initial Temperature differences between liquid and isothermal bath :

Heating→ 5 - 15°K

Cooling→ 5 – 15°K

RESULTS & DISCUSSION:

Noting that condensed milk can be rheologically identified as power law fluid with the parameters consistency index (k), flow behavior index (n), k & n are expected to vary with temperature and composition. Therefore cooling and heating characteristics (Temperature distribution, heat flux distribution and heat transfer coefficients) are unlikely to be similar to Newtonian fluids.

Cooling Effect:

The temperature distributions for ΔT of 5°K, 10°K, 15°K are shown in Fig(2). Significant variation in the slope of the curves is seen. Temperature distributions at 5 min, 25 min, 45 min, 60 min & 80 min are presented separately in Fig(3).

The temperature distribution is a near smooth curve for the lowest temperature difference of 5°K. The variation in the dimensionless temperature is more significant near the wall and is rather limited to within 5% in the core of the liquid.

Heat flux variation at the wall is smooth and decreases with time as expected. Heat flux at the wall increases with ΔT and cooling time is seen to increase with ΔT (Fig. 4). It is also observed that except for the initial times where heat flux changes rapidly, the heat flux remains almost near uniform over significant time of cooling. Considering the high apparent viscosity of condensed milk (>2000), one anticipates low convection. Unsteady conduction model is applicable for times <10min [3]. However significant deviations(as high as 50%) except very close to the wall surface were observed.

Heat transfer coefficient has been defined as

$$h = \frac{-k\,(dT/dr)_w}{(T_c - T_w)_{initial}}$$

k – thermal conductivity (W/m°K)

Tc – Center temperature (°K)

Tw – Wall temperature (°K)

based on initial temperature difference between the center and metal surface. In the calculations thermal resistance of water side is neglected.

Variation of heat transfer coefficients (Fig. 5) show a continuous decrease with time. This is in fact the same trend as that of heat flux. Initial period show h increasing with ΔT for $t<15$min.

<u>Heating Effect:</u>

The dimensionless temperature distributions are shown for $\Delta T = 5°K$, $10°K$ and $15°K$ in figures 5 & 6. It is seen clearly from figure 6 that for all the times the temperature variations are more significant near the wall. The variation with in the core of the container is in general small in comparison. The temperature differences at any radial position are more significant in case of cooling than in case of heating.

The variation of heat flux and heat transfer coefficient show rapid decrease until 20 min of heating and the variation for rest of heating is small.

A maximum deviation of about 50% in the heat flux and heat transfer coefficients occur for the time below 20 min.

<u>Concentration Effect:</u>

The temperature gradient variation with time clearly indicate the effect of concentration which reduces the total cooling time with increase in dilution. One obvious property influencing the heat transfer rate is apparent viscosity and coefficient of expansion.

The temperature profiles show a transition from weak natural convection (Fig. 9) to stronger natural convection (Fig. 12). Dimensionless temperature at a dimensionless radius of 0.44 show a dip in temperature. More stronger effect of natural convection is seen for water even at ΔT of 5°K (Fig. 13).

General characteristics for all dilutions show a rapid decrease with time and continuation of the decrease for diluted condensed milk. This characteristic is more closer to the variations for water. More significantly, the variation for 100% condensed milk is negligible after 20 min.

Conclusions:

1. Temperature distributions for pure condensed milk and dilutions up to 50% show strong variation.
2. The characteristics of heat flux and heat transfer coefficients differ for cooling and heating experiments.The general trend of data broadly is as anticipated on the basis of apparent viscosity.
3. .No correlation is attempted as accurate thermophysical properties need to be obtained

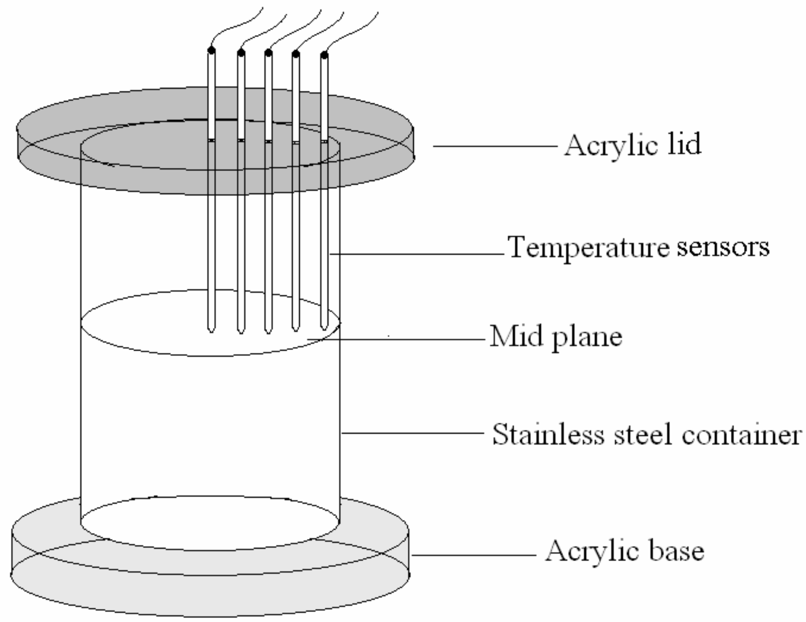

Fig. 1: Experimental container

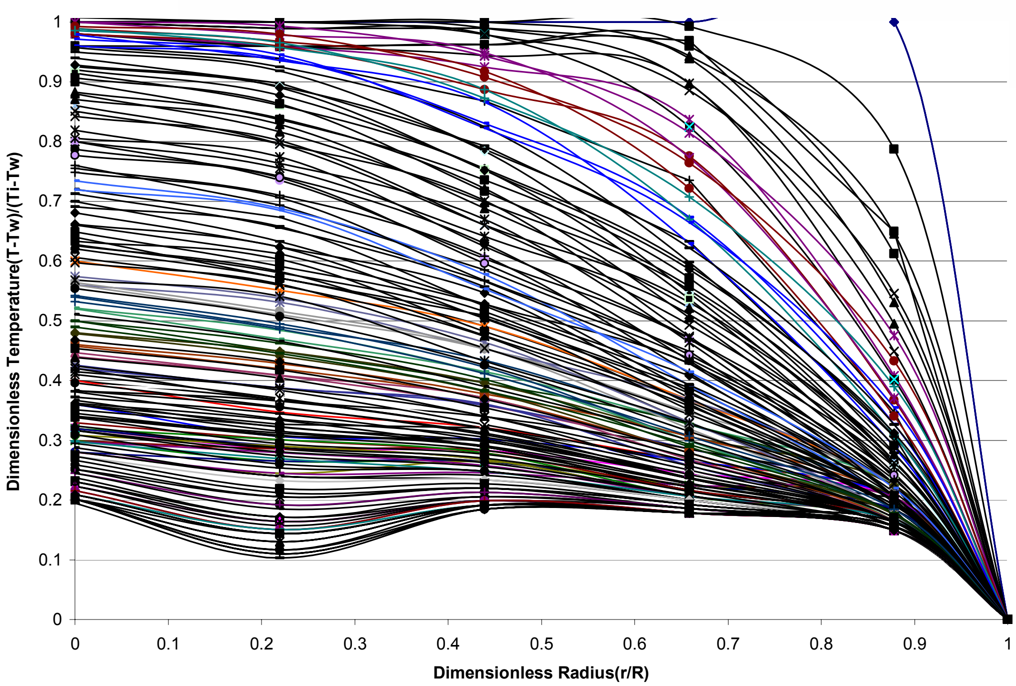

Fig 2. Dimensionless temperature distribution along radial direction for every 2 min ranging from 0 to 80 mins for ΔT = 5°K, 10°K, 15°K during cooing.

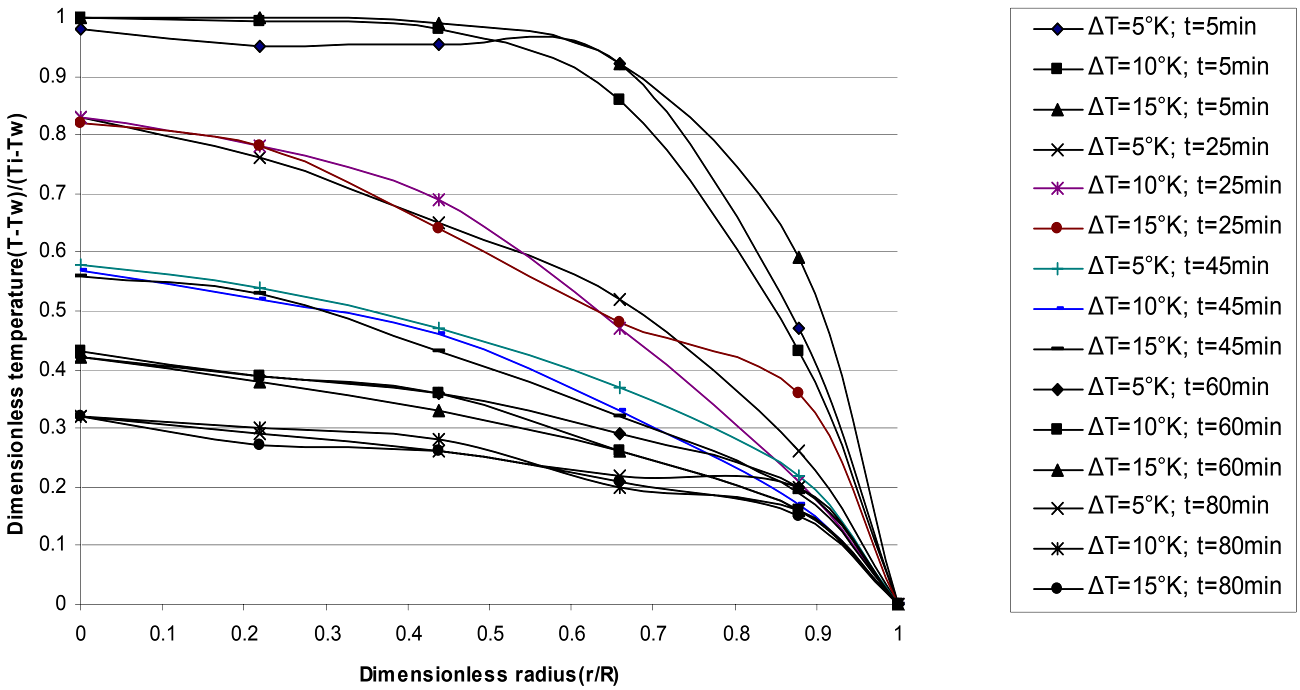

Fig 3. Dimensionless temperature distribution along radial direction at specified times for ΔT = 5°K, 10°K, 15°K during cooling.

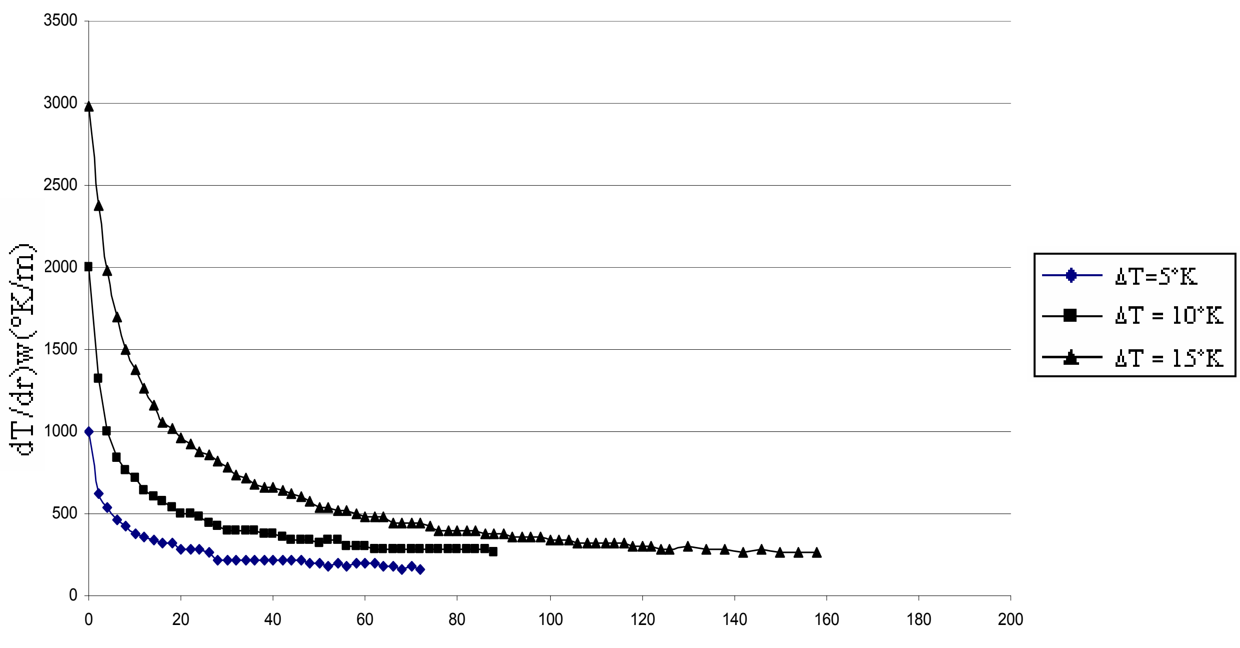

Fig 4. Comparison of variation of temperature gradients with time at the wall for ΔT = 5°K, 10°K, 15°K during cooling .

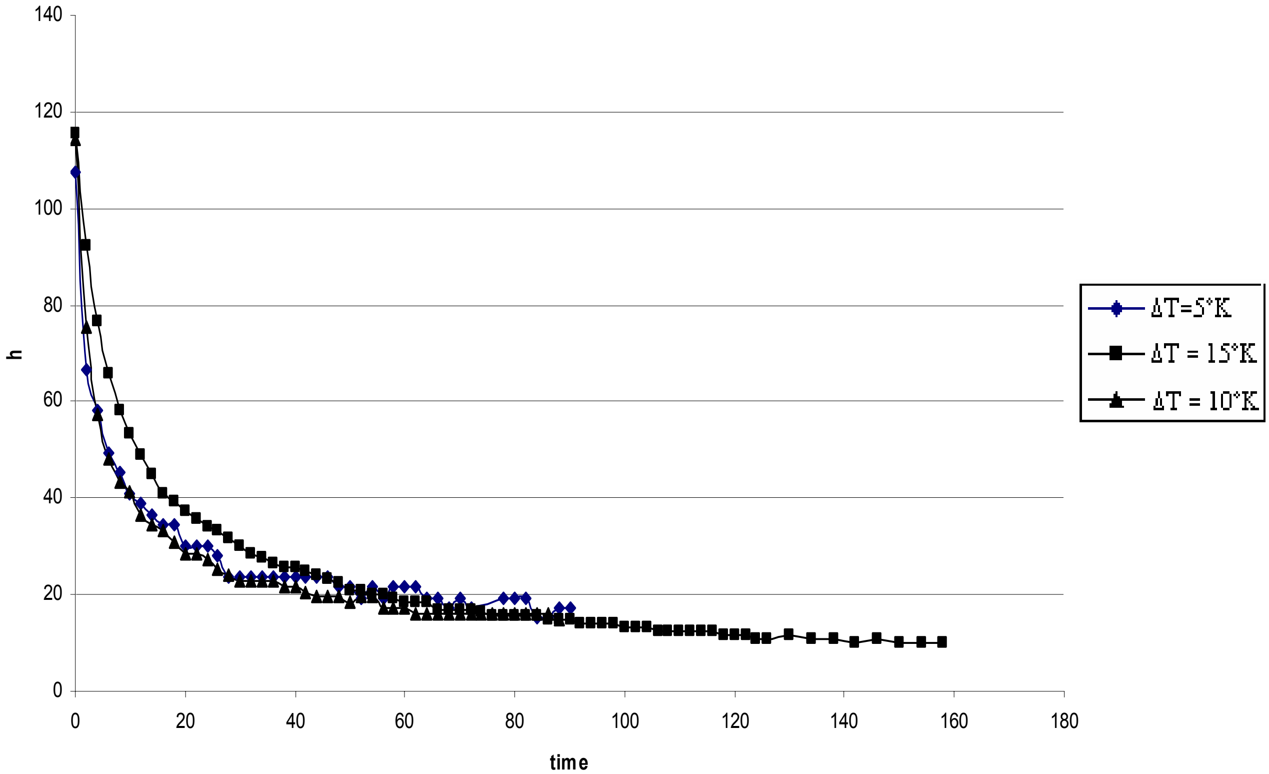

Fig 5. Comparison of Heat transfer coefficients for $\Delta T = 5°K, 10°K, 15°K$ during cooling .

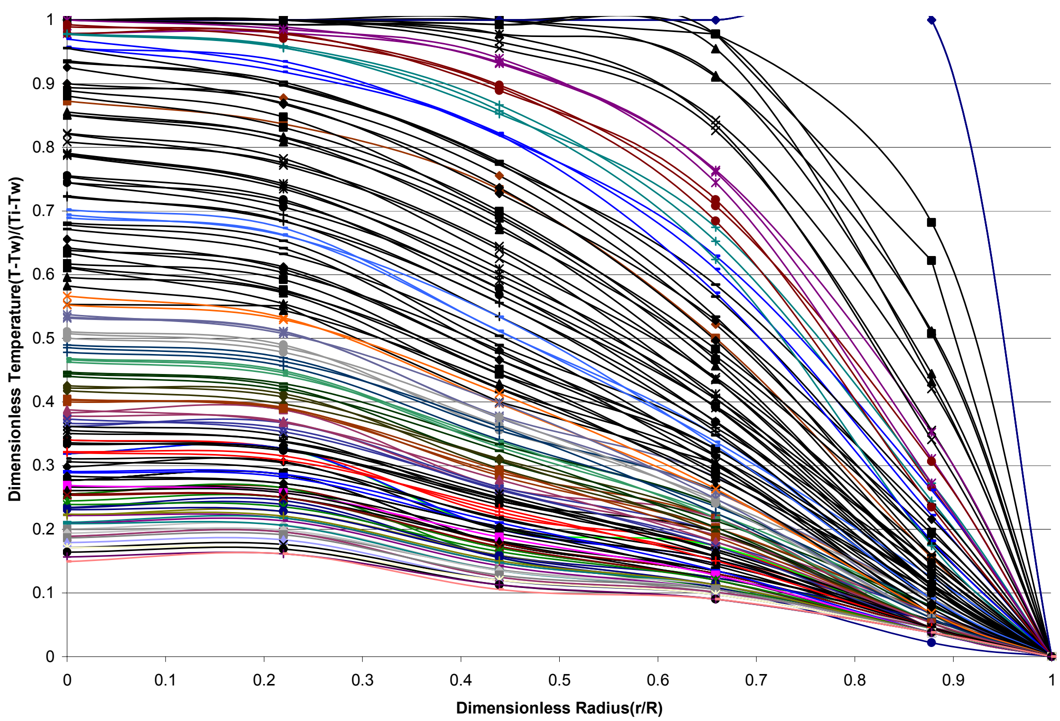

Fig 5. Dimensionless temperature distribution along radial direction for every 2 min ranging from 0-80 min for $\Delta T = 5°K, 10°K, 15°K$ during heating.

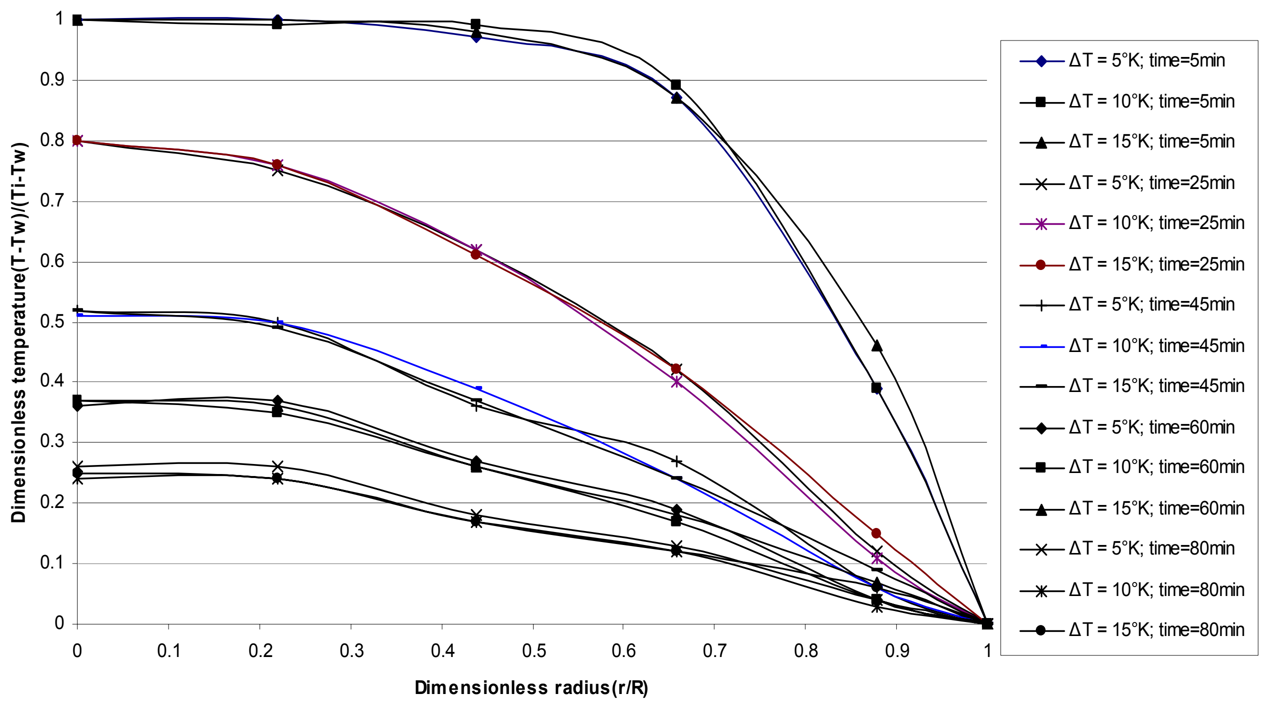

Fig 6. Dimensionless temperature distribution along radial direction at specified times for

ΔT = 5°K, 10°K, 15°K during heating

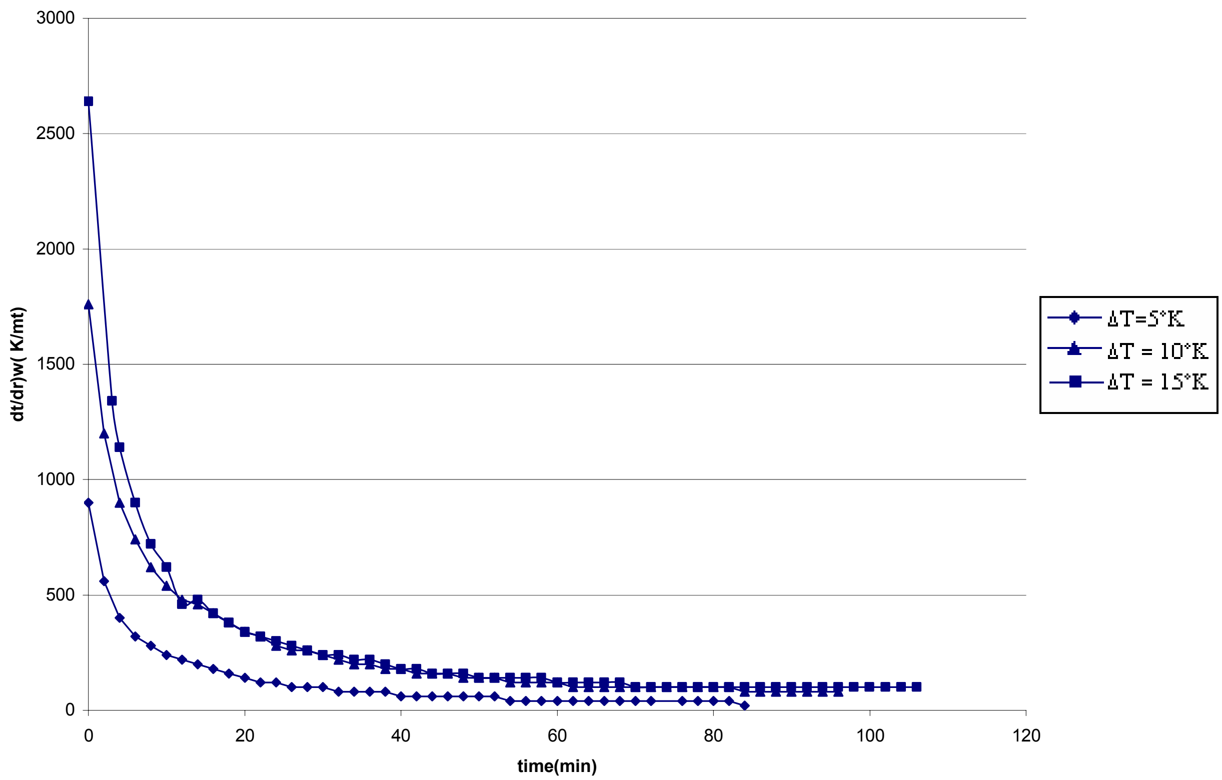

Fig 7. Comparison of variation of temperature gradients with time at the wall for ΔT = 5°K, 10°K, 15°K during heating .

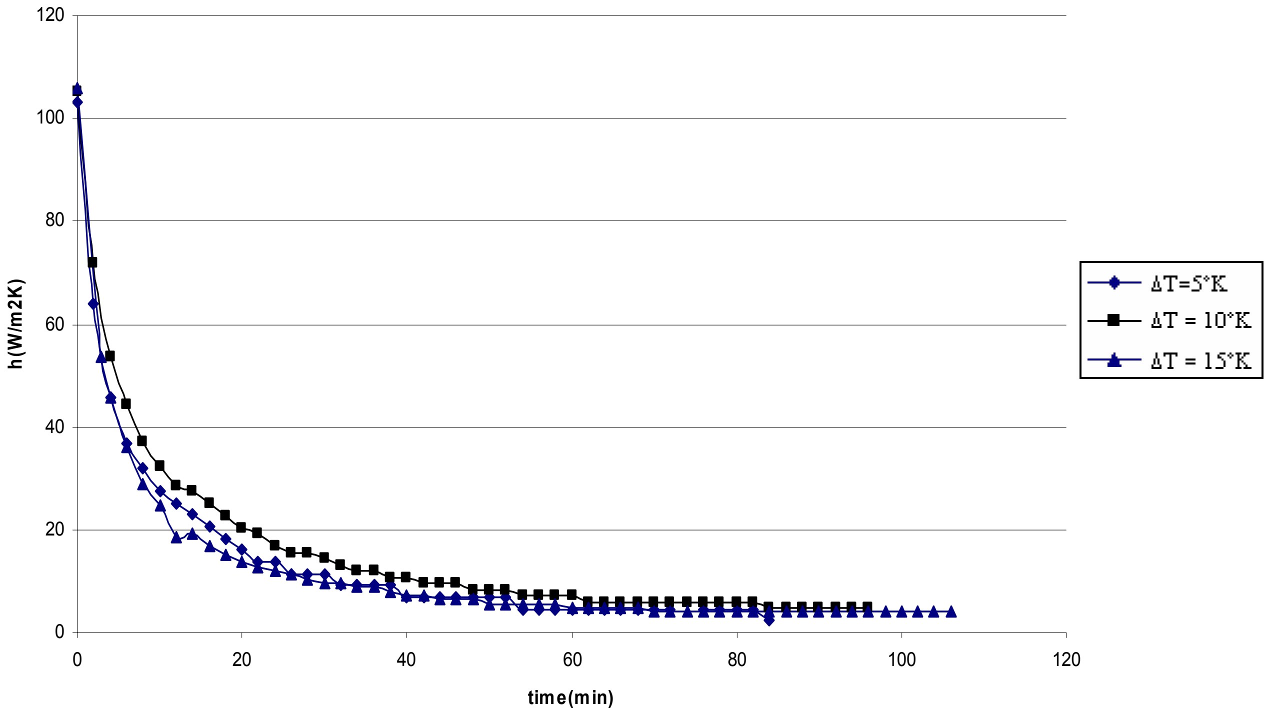

Fig 8. Comparison of Heat transfer coefficients for ΔT = 5°K, 10°K, 15°K during heating
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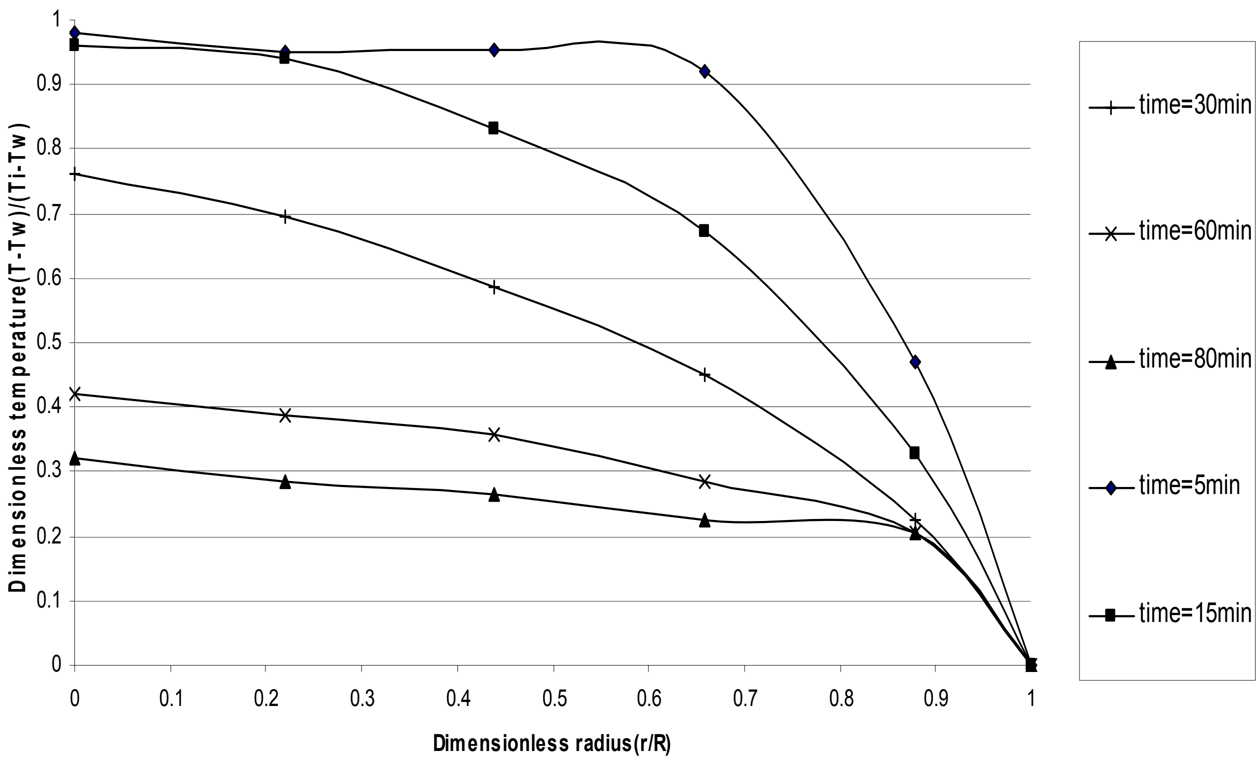

Fig. 9: Dimensionless temperature distribution at specified time for condensed milk of 100% volumetric composition.

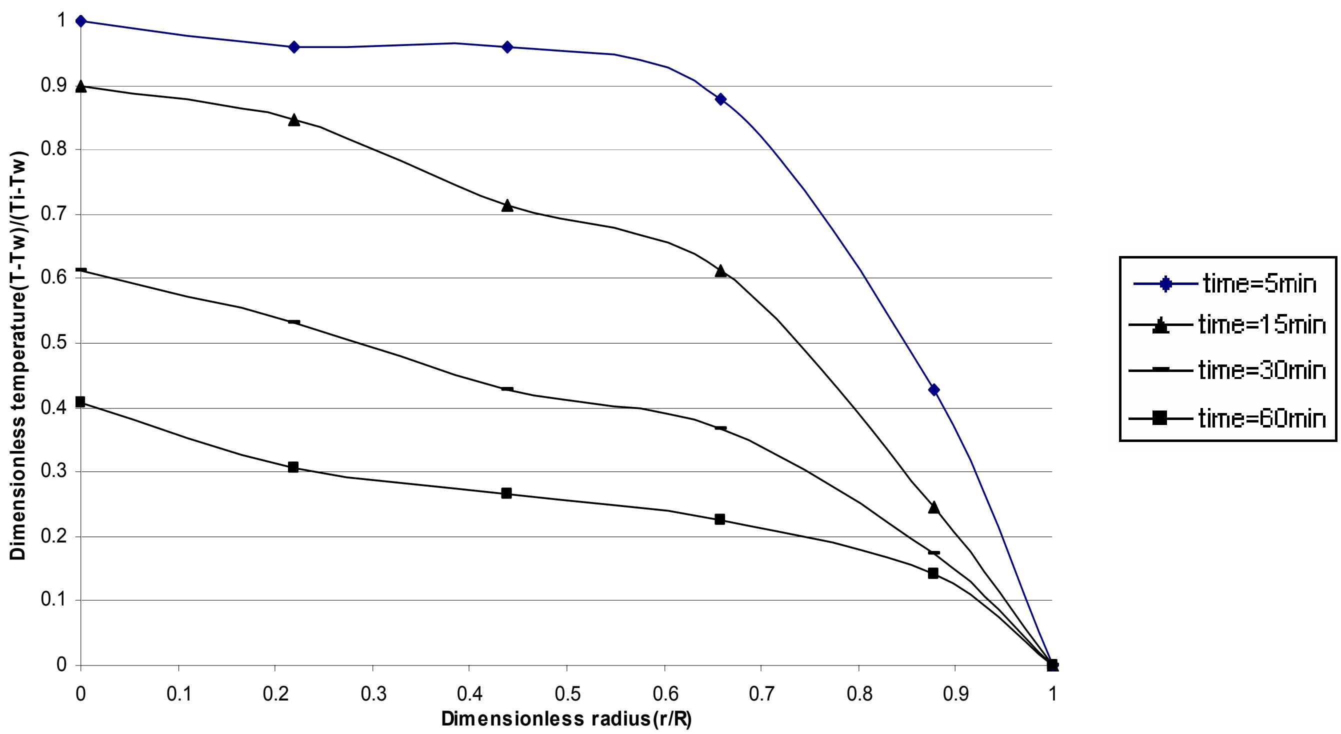

Fig. 10: Dimensionless temperature distribution at specified time for condensed milk of 90% volumetric composition.

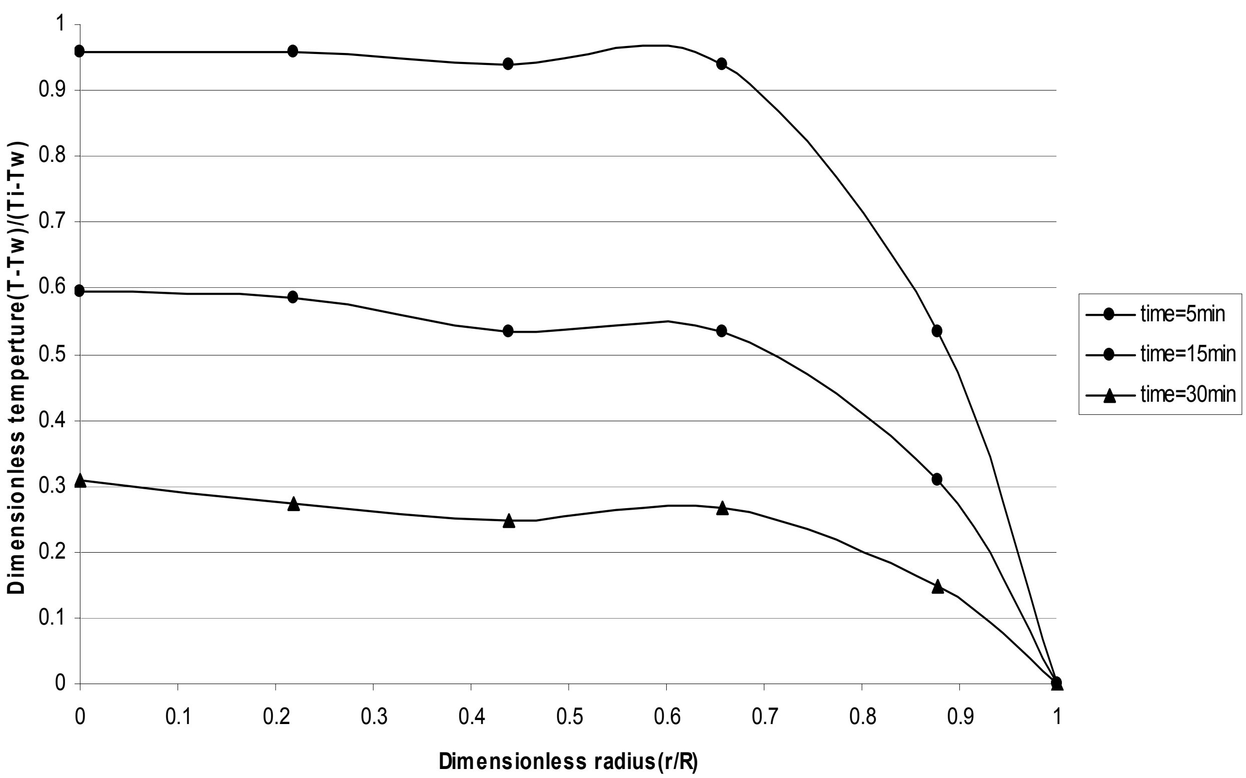

Fig. 11: Dimensionless temperature distribution at specified time for condensed milk of 80% volumetric composition.

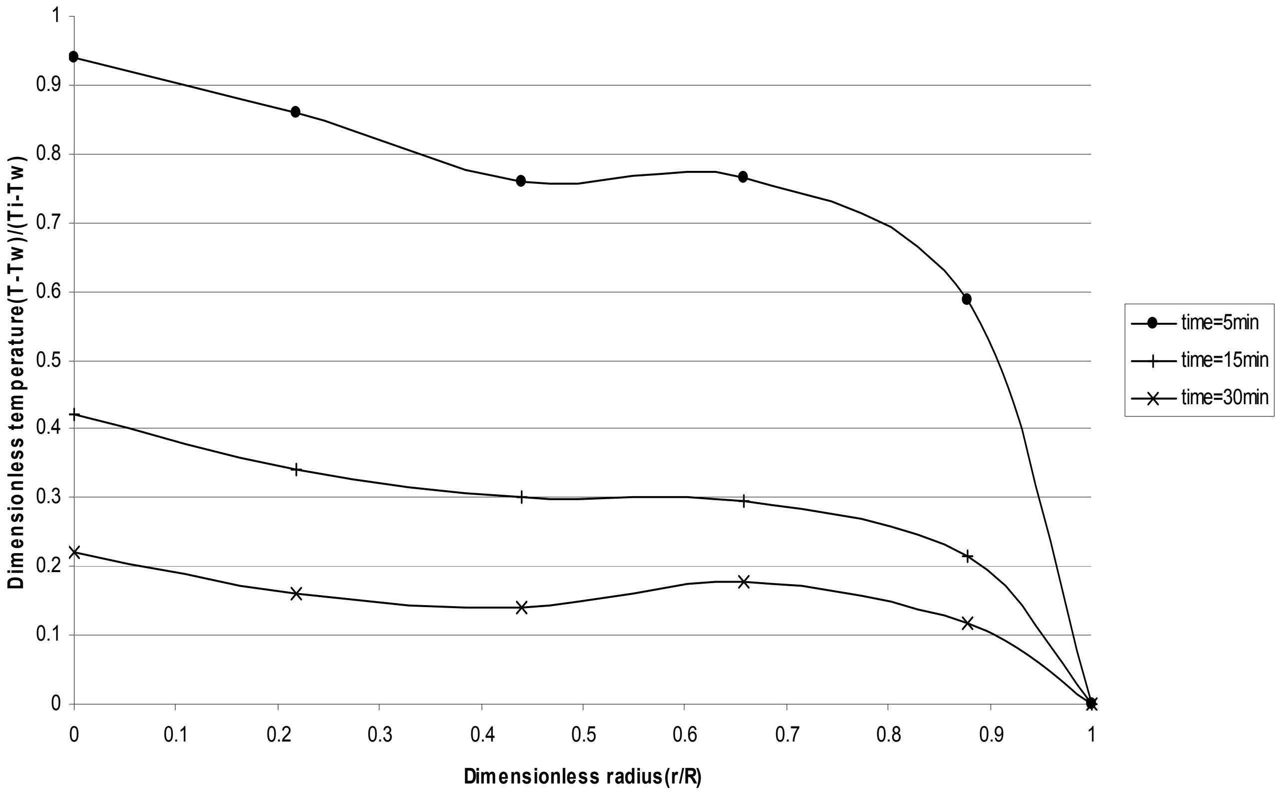

Fig. 12: Dimensionless temperature distribution at specified time for condensed milk of 50% volumetric composition.

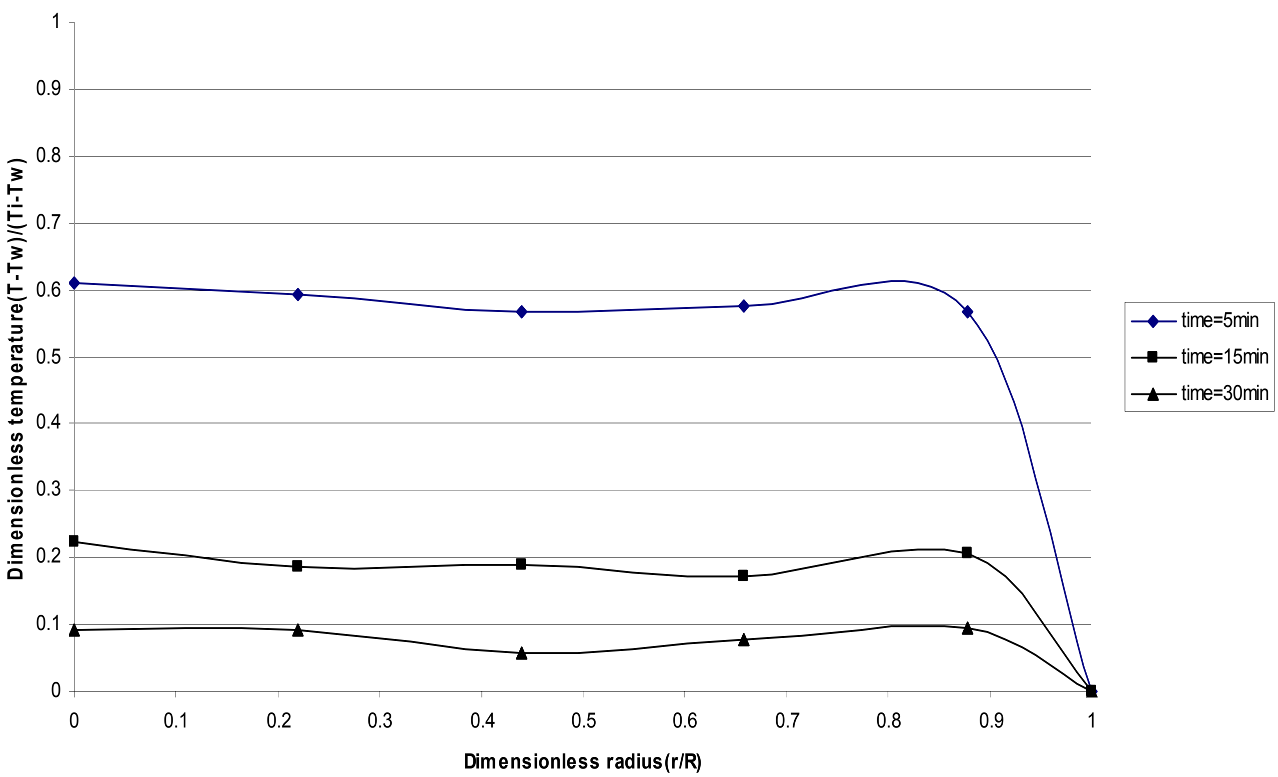

Fig. 13: Dimensionless temperature distribution at specified time for water.

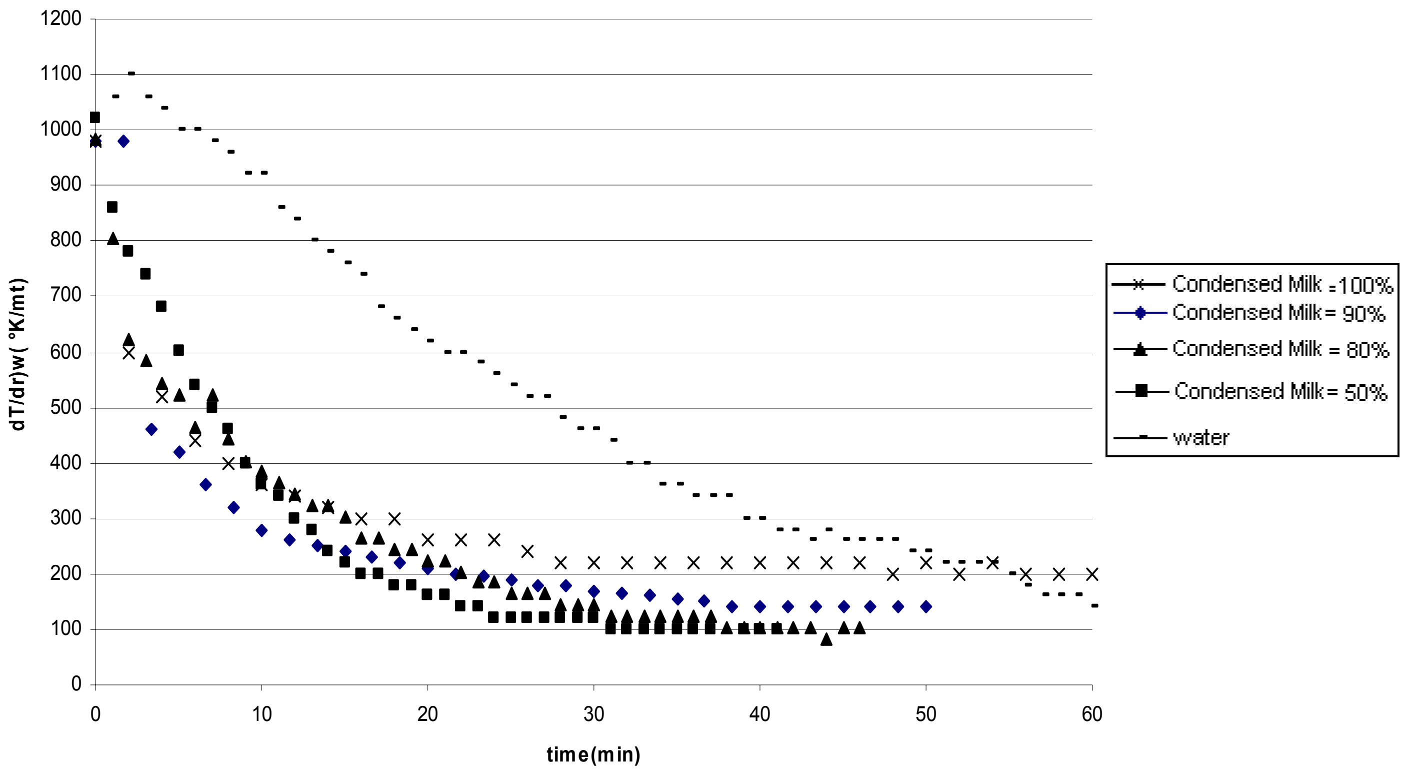

Fig 14. Comparison of temperature gradients at the wall for different dilutions during cooling and ΔT = 5 °K

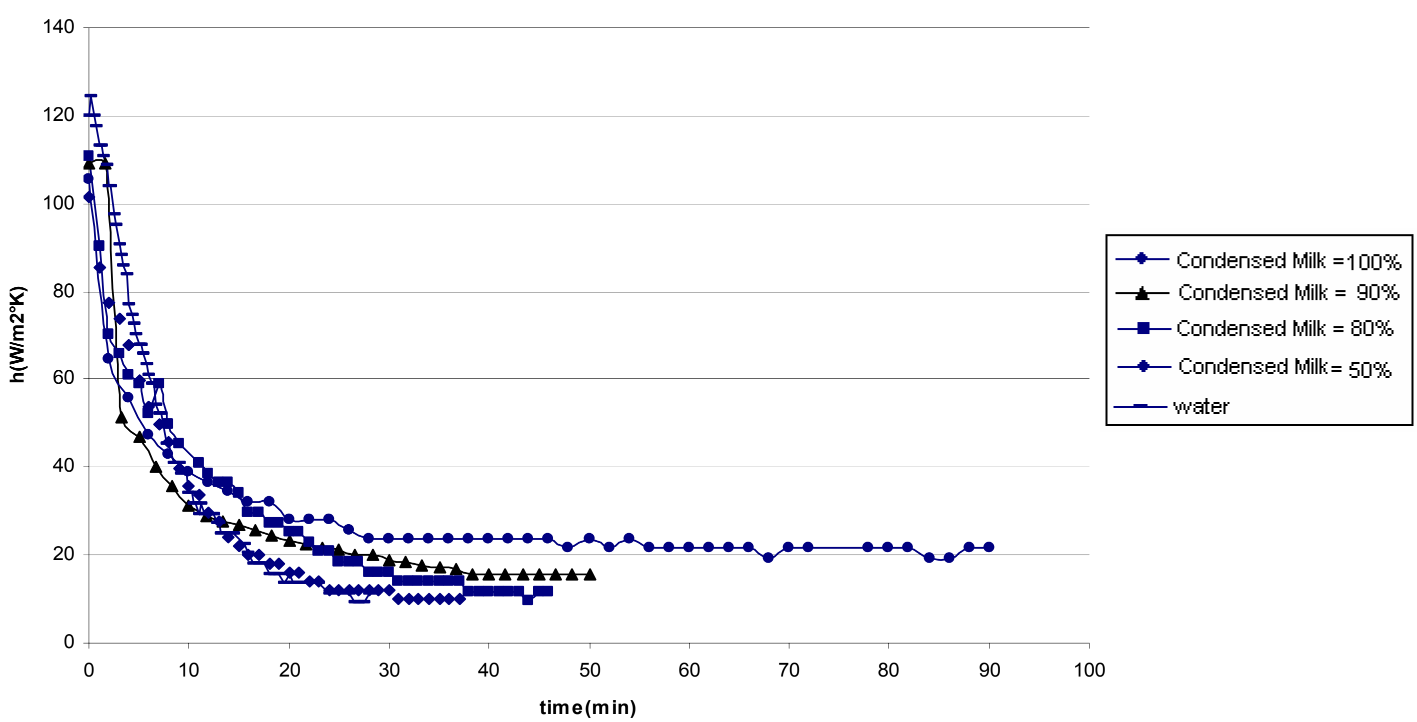

Fig 15. Comparison of Heat transfer coefficients between 100%, 90%, 80%, 50% volumetric compositions during cooling and for ΔT = 5 °K

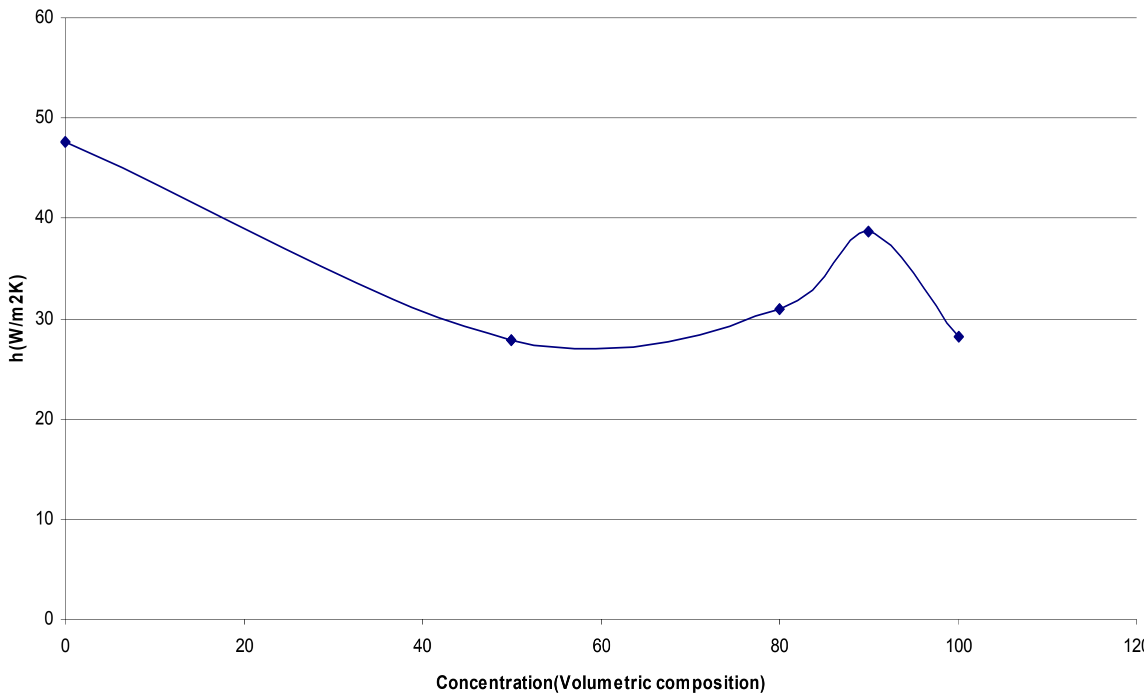

Fig 16. Variation of Heat transfer coefficient with concentration (% volumetric composition)

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