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D.R. HELDMAN  
and  
R.P. SINGH  
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# **PARTICLE/FLUID INTERFACE HEAT TRANSFER UNDER UHT CONDITIONS AT LOW PARTICLE/FLUID RELATIVE VELOCITIES<sup>1</sup>**

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## **ABSTRACT**

*Mathematical models are often used for determining commercial thermal process schedules for heterogeneous foods processed in an aseptic processing system. The particle/fluid interface convective heat transfer coefficient is a critical input parameter for these models and must be determined experimentally. Experiments were conducted at 129.4°C in a specially designed apparatus to determine the particle/fluid interface convective heat transfer coefficient for model food particles heated by Newtonian and non-Newtonian fluids. Values of the heat transfer coefficient ranged between 55.63 and 89.5 W/m<sup>2</sup>°C for particles heated in a non-Newtonian fluid and between 65.67 and 107.11 W/m<sup>2</sup>°C for particles heated in a Newtonian fluid.*

## **INTRODUCTION**

Aseptically processed and packaged shelf stable foods have made significant inroads into the marketplace. The improved quality possible with this type of process technology along with improved equipment design and attractive packaging has made this possible.

However, heterogeneous products containing discrete particles (e.g., clam chowder) have apparently not benefited from this technology; no such products have been introduced into the marketplace as yet. Part of the problem is the

<sup>1</sup>Scientific Article Number A4897, Contribution Number 7935 of the Maryland Agricultural Experimental Station (Department of Agricultural Engineering).



difficulty involved with determining an appropriate thermal process to assure safety while at the same time minimizing nutrient and quality loss. Traditionally, thermal processes for in-container retorted foods are determined by combining microbial destruction kinetics data with food product heating rate data obtained from heat penetration testing (NCA 1968). Nutrient and quality destruction can be minimized with an appropriate thermal process schedule (Teixeira *et al.* 1969). Heat penetration testing of the particulate matter portion of heterogeneous foods processed in an aseptic processing system is currently impractical. Consequently, process schedule determination must be based on other methods. One possible method is mathematical modeling combined with appropriate input data obtained experimentally. Several such models have been reported in literature (de Ruyter and Brunet 1973; Hampton 1972; Manson and Cullen 1974; Snyder 1986; Sastry 1986; Chandarana and Gavin 1989; Chandarana *et al.* 1989 and Chandarana 1988). These models predict the heating rate of the particulate portion and consequent lethality accumulation.

The heating rate of the particulate portion is a function of the boundary layer surrounding the particle (Manson and Cullen 1974; Sastry 1986; Chandarana *et al.* 1989). The boundary layer around the particle is often characterized in the form of a heat transfer coefficient referred to as the particle/fluid interface convective heat transfer coefficient ( $h_p$ ). In order to determine the optimum thermal process, this heat transfer coefficient must be determined experimentally under conditions that closely approximate the actual situation within an aseptic processing system. However, approximating the actual situation within an aseptic processing system is impractical because particle center temperature, as it travels through the system, cannot be monitored with currently available equipment. Thus, conservative experimental methods must be used (Chandarana *et al.* 1989). Dignan *et al.* (1989) indicated that experimental determination of the particle/fluid interface convective heat transfer coefficient under a condition of zero relative velocity between the particles and fluid would be conservative from a regulatory stand point. Chandarana *et al.* (1989) experimentally determined the particle/fluid interface convective heat transfer coefficients at 135°C with the particle and fluid held stationary with respect to each other. Their data indicates that the particle/fluid interface convective heat transfer coefficient so determined is quite low; between 8.1 and 35.0 W/m<sup>2</sup>°C for non-Newtonian fluids and 51.1 W/m<sup>2</sup>°C for water. If such low values are used for predicting lethal effect of an actual process while determining a process schedule, product of poor quality may result (Chandarana *et al.* 1989). Sastry *et al.* (1989) reported that in a real hold tube, absolute zero particle/fluid relative velocity may be hypothetical and demonstrated with an ingenious method that particle/fluid interface convective heat transfer coefficients may be quite high. Sastry *et al.* (1989) data actually compare favorably with that of Heppell (1985). Zuritz *et al.* (1987) also determined the particle/fluid interface convective heat transfer coefficient in a sim-

ulated hold tube. Mushroom shaped particles were used. They reported that the particle/fluid interface convective heat transfer coefficient ranged between 548 and 1175 W/m<sup>2</sup>C, depending on particle size and fluid flow dynamics in a hold tube of fixed diameter. The apparent dependence of  $h_p$  on particle size in Zuritz *et al.* work was as a result of using different size particles within a fixed diameter holding tube. Thus, as the particle diameter increased, the fluid flow cross section decreased, increasing the instantaneous velocity at the particle surface. This enhanced local convection resulted in a higher calculated  $h_p$  value as particle dimension increased.

Flow dynamics of two phase particle/fluid flow are quite complex. No literature data is available that conclusively quantifies the particle/fluid interaction in an aseptic processing system. As such data becomes more available, particle/fluid interface convective heat transfer coefficient determined at various particle/fluid relative velocities and aseptic processing temperatures will become more useful. Special laboratory apparatus such as the one described by Chandarana *et al.* (1989) and Chandarana (1988) is necessary to determine the particle/fluid interface convective heat transfer coefficient at aseptic processing temperatures. This paper presents experimental data on particle/fluid interface convective heat transfer coefficient determined at an aseptic processing temperature for starch solutions and water flowing past model food particles.

## MATERIALS AND METHODS

### Experimental Apparatus

A process simulator was designed as a joint effort between the National Food Processors Association (NFPA) and Cherry-Burrell Corporation (CB). The simulator was fabricated by CB. A flow schematic of the process simulator is shown in Fig. 1.

The process simulator system particulate test fixture consists of a 14.7 cm diameter cylindrical stainless steel chamber. The test fixture contains six particulate immobilization chambers so designed that the process fluid can completely surround the particles under test (Fig. 2). The bottom of the test fixture has a perforated baffle plate through which the fluid enters. The baffle plate aids in reducing the fluid entrance turbulence. Each immobilization chamber is instrumented with a subminiature type T (copper-constantan) thermocouple (Omega SCPSS-020G-6) which can be embedded in the particle. The process fluid is heated in an indirect heating loop consisting of two shell and tube heat exchangers, HE1 and HE2 (Fig. 1). HE2 is used to heat water in a closed loop, using steam as the heating medium. This water is the heating medium in HE1 which is used for heating the process fluid. Such an indirect heating loop results in a better control of the process fluid temperature.

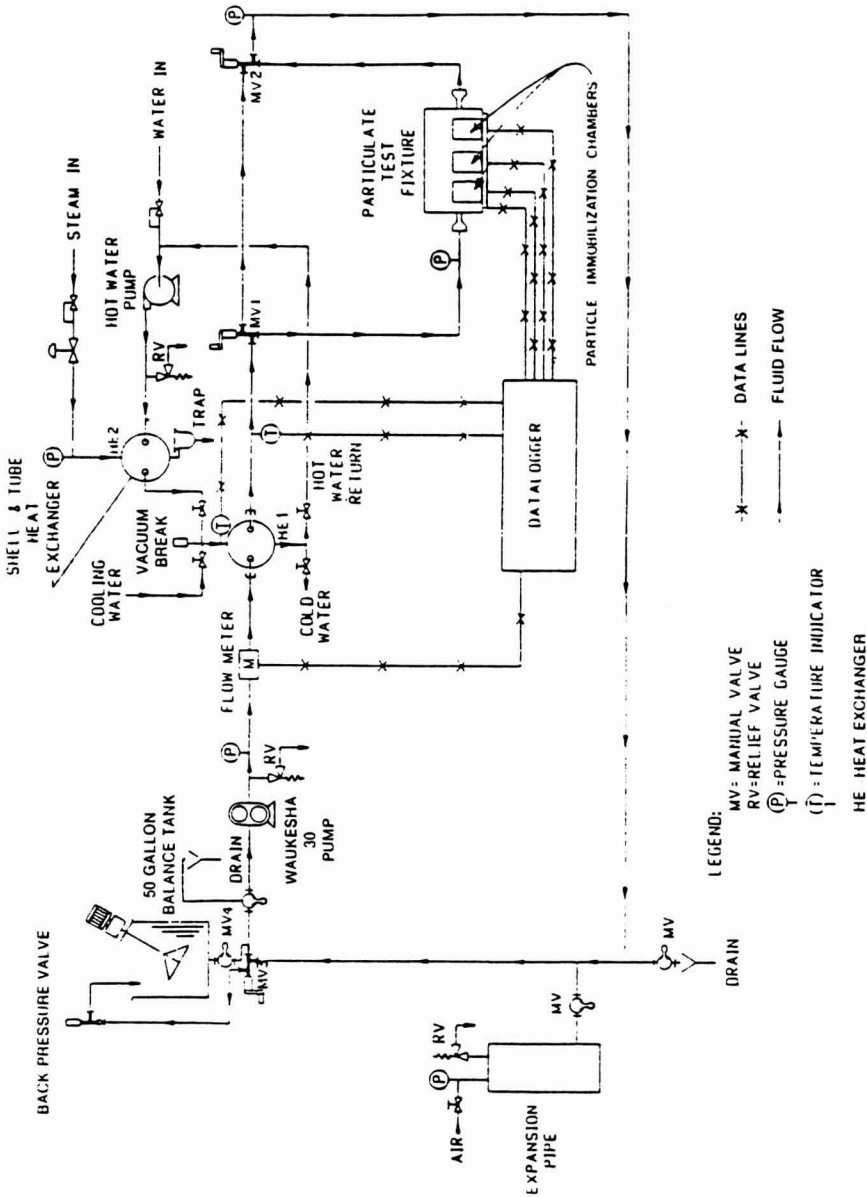


FIG. 1. SCHEMATIC OF THE PROCESS SIMULATOR USED FOR THE PARTICLE HEAT TRANSFER STUDIES (Courtesy of Cherry Burrell Corp.)

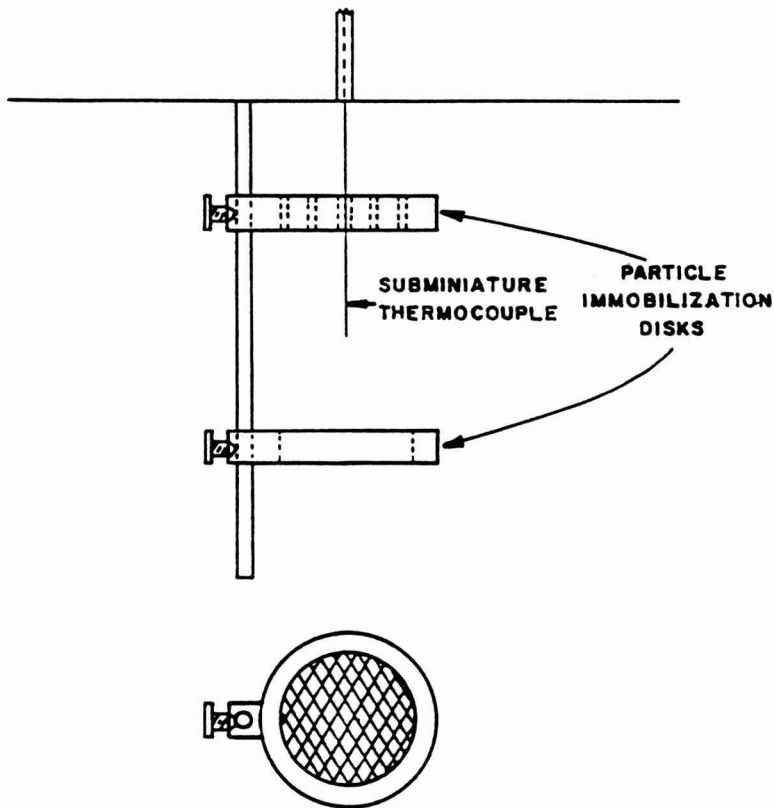


FIG. 2. SCHEMATIC OF THE PARTICLE IMMOBILIZATION CHAMBER

There are four different paths for the process fluid through the process simulator system. Initially the fluid is pumped out of the 50 gallon balance tank, Fig. 1, through HE1 and MV1 to MV2 (by-passing the particulate test fixture), and returned to the balance tank. The fluid can also be recirculated within the system without returning to the balance tank by properly repositioning the three-way manual valve MV3. The expansion pipe with overriding air pressure is used to pressurize the process fluid so that the flashing can be prevented while heating fluids to temperatures above their boiling points at atmospheric pressure. Once the fluid has reached a predetermined temperature, the fluid can be introduced into the particulate test fixture by repositioning the three-way manual valves MV1 and MV2 so that the fluid travels through the test fixture.

## Experimental Methods

Heat transfer studies were performed with a non-Newtonian fluid (2–3% w/w starch solution) and water flowing past specially constructed silicone cubes (GE RTV627) with a type T (copper-constantan) thermocouple located at the geometric center (Fig. 3). The thermocouples used were high accuracy thermocouples ( $\pm 0.5^\circ\text{C}$ ) manufactured by Omega Engineering, Stamford, CT (model TT-T-24SLE).

The test fluid was prepared by mixing an appropriate quantity of Thermflo (National Starch Co.) starch and water. The mixture was heated to  $93.3^\circ\text{C}$  ( $200^\circ\text{F}$ ) for 30 min in the simulator system by recirculating in and out of the balance tank. The fluid was then heated to  $115.6^\circ\text{C}$  ( $240^\circ\text{F}$ ) and held for 10 min (until the starch was gelatinized). The particulate test fixture was by-passed during the starch gelatinization process. The fluid was then heated to the final experimental temperature. Once the fluid temperature reached  $129.4^\circ\text{C}$  ( $265^\circ\text{F}$ ), the position of manual valves MV1 and MV2 (Fig. 1) was changed so as to pump the gelatinized starch into the simulator chamber.

The thermal properties of the fluid used in the experimental research are listed in Table 1. Thermal conductivity and diffusivity of the silicone were determined experimentally by Thermal Technologies, Inc. (Boston, MA) and are shown below where as the silicone density and specific heat used were provided by the manufacturer and are  $1370\text{ kg/m}^3$  and  $1.47\text{ kJ/kg}^\circ\text{C}$ , respectively.

$$k_p = 0.381 - 5.67 \times 10^{-4} T \quad (1)$$

$$\alpha_p = 3.27 \times 10^{-7} - 4.876 \times 10^{-10} T \quad (2)$$

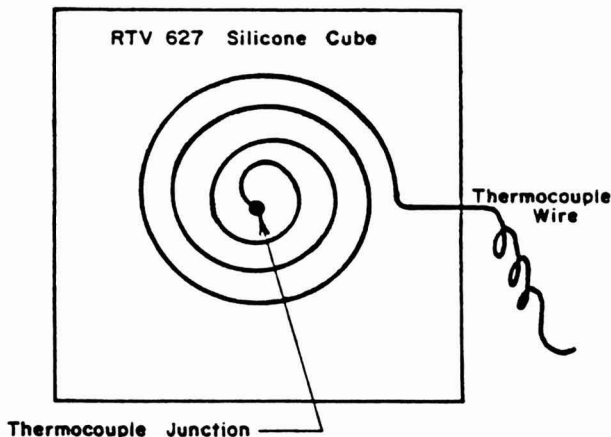


FIG. 3. SILICONE CUBE WITH EMBEDDED THERMOCOUPLE WIRE, COILED TO REDUCE CONDUCTION ALONG WIRE, USED IN HEAT TRANSFER STUDIES

TABLE 1.  
PROPERTIES OF FLUIDS USED IN HEAT TRANSFER AND  
COEFFICIENT DETERMINATION

Fluid	Concentration %	Specific Heat kJ/kg <sup>o</sup> C	Thermal Conductivity W/m <sup>o</sup> C
Starch Solution	2-3	4.13 <sup>a</sup>	0.61 <sup>b</sup>
Water		4.18 <sup>c</sup>	0.62 <sup>c</sup>

<sup>a</sup>Heldman and Singh (1981)

<sup>b</sup>Choi and Okos (1986)

<sup>c</sup>Holman (1976)

The data acquisition and control system associated with the process simulator (Keithley, Series 500) was capable of monitoring temperature at several points in the system and flow rate at a user selectable frequency. The temperature of the particle center, surrounding fluid in close proximity of the particle (within 1 cm), and flow rate was recorded at a frequency of 1 Hz throughout the experiment. Brooks Wafer-Mag flow meter (7400 series) was used for flow rate monitoring.

The starch solution was assumed to follow the Power Law model (Rao 1986). Brookfield LVT rotoviscometer with a small sample adapter (Brookfield Engineering Labs, Stoughton, MA) was used for determining the rheological parameters of the starch solutions, shown on Table 2.

### Heat Transfer Coefficient Calculations

The heat transfer into the particle under the experimental conditions described earlier (cartesian coordinates) can be represented as follows:

$$\frac{\partial T}{\partial t} = \frac{k_p}{\rho c_p} \left[ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right] \quad (3)$$

where  $T = T(x,y,z,t)$

$T_r = T_r(t)$

TABLE 2.  
CONVECTIVE HEAT TRANSFER COEFFICIENT FOR STARCH SOLUTIONS  
FLOWING PAST A 25.4 MM SILICONE CUBE

Flow <sup>a</sup> Behavior Index	Consistency <sup>a</sup> Coefficient	Part./Fluid Relative Velocity	Reynolds Number	Prandtl Number	Part./Fluid <sup>b</sup> Convective Heat Trans. Coefficient		Nusselt Number
n	K Pa s <sup>n</sup>	cm/s	Re	Pr	$h_p$ W/m <sup>2</sup> °C	Std. Dev.	Nu
0.78	4.20x10 <sup>-3</sup>	0.44	27.38	9.47	67.62	2.07	2.82
0.97	1.35x10 <sup>-2</sup>	0.52	9.95	23.65	67.44	3.69	2.81
0.92	1.20x10 <sup>-2</sup>	0.68	15.15	21.78	74.47	2.91	3.10
0.99	8.60x10 <sup>-3</sup>	0.85	25.67	14.65	85.47	3.80	3.56
0.82	3.26x10 <sup>-2</sup>	0.93	8.50	60.98	80.86	4.49	3.37
0.94	1.28x10 <sup>-2</sup>	1.16	24.80	22.11	89.50	6.77	3.73
1.0	1.66x10 <sup>-2</sup>	0.44	6.83	28.10	55.63	2.38	2.32
0.96	1.08x10 <sup>-1</sup>	0.63	1.55	189.85	61.01	3.80	2.54
0.97	5.05x10 <sup>-2</sup>	0.77	4.03	87.42	65.43	7.12	2.72
0.86	2.04x10 <sup>-1</sup>	0.88	1.23	376.18	63.98	2.68	2.66

<sup>a</sup>At 30°C

<sup>b</sup>Each value is a mean of seven (7)

with the initial conditions  $T(x,y,z,0) = T_i$   
and the boundary conditions:

$$k_p \frac{\partial T}{\partial x} = h_p (T_f - T) \quad x = X \text{ (surface)}$$

$$\frac{\partial T}{\partial x} = 0 \quad x = 0 \text{ (center)}$$

$$k_p \frac{\partial T}{\partial y} = h_p (T_f - T) \quad y = Y \text{ (surface)}$$

$$\frac{\partial T}{\partial y} = 0 \quad y = 0 \text{ (center)}$$

$$k_p \frac{\partial T}{\partial z} = h_p (T_f - T) \quad z = z \text{ (surface)}$$

$$\frac{\partial T}{\partial z} = 0 \quad z = 0 \text{ (center)}$$

$$T(x, y, z, t) \leq T_f(t)$$

Based on an initial guess value of  $h_p$  and experimental fluid temperature,  $T_f(t)$ , a set of particle center temperatures  $T_c(t)$  were calculated by solving Eq. 3 numerically using an explicit finite difference scheme. The computed values,  $T_c(t)$  were compared with observed values  $T_o(t)$  and a standardized sum of the difference (SSSD) was calculated as shown in Eq. 4. The value of  $h_p$  was iteratively adjusted and the above procedure repeated until the SSSD was minimized. The value of  $h_p$  that results in a minimum SSSD is then the convective heat transfer coefficient at the particle fluid interface under the given test conditions.

$$\text{SSSD} = \frac{\sum_{i=1}^{nn} (T_c(t) - T_o(t))^2}{nn} \quad (4)$$

$nn$  = number of observations

### Data Analysis

The particle/fluid interface convective heat transfer coefficient ( $h_p$ ) is a function of the thermophysical properties of the fluid and the fluid flow dynamics. Zuritz *et al.* (1987) related experimental Nusselt number to Reynolds and Prandtl numbers. A similar approach is taken in reporting our experimental results so that a relationship such as the one shown in Eq. 5 is determined. Regression analysis was used to determine this relationship. SYSTAT (SYSTAT, Inc., Evanston, IL) statistical package for IBM-PC and compatibles was used for the analysis. For water, however,  $Nu$  was evaluated as a function of  $Re$  alone since at any given temperature,  $Pr$  is a fixed value.

$$Nu = f(Re, Pr) \quad (5)$$

## RESULTS AND DISCUSSION

Figures 4 and 5 are typical time-temperature profiles showing the experimental fluid temperature, experimental particle center temperature, and predicted particle



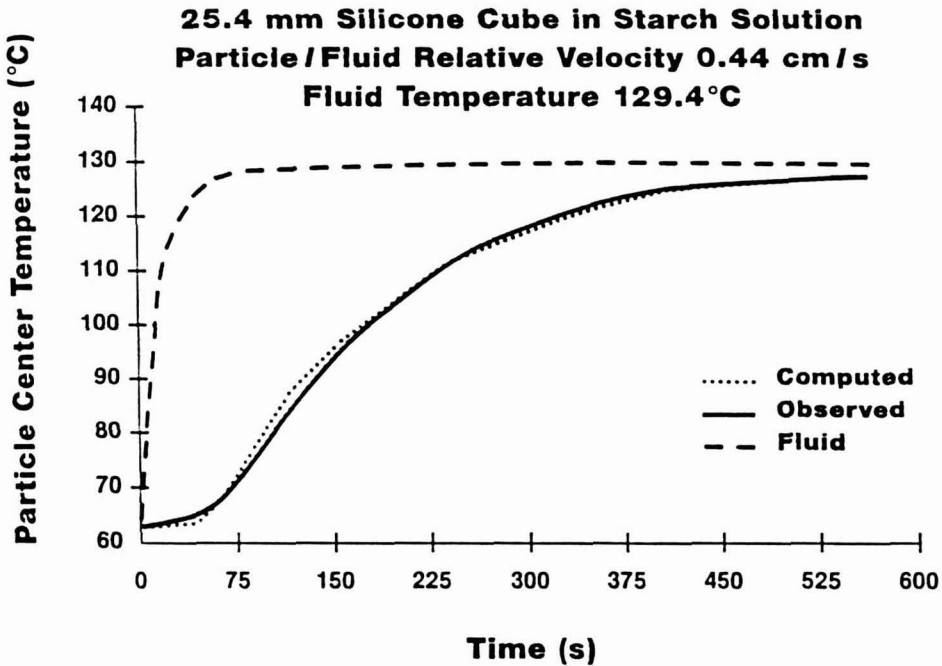


FIG. 4. TYPICAL TIME TEMPERATURE PROFILE FOR HEATING A 25.4 MM SILICONE CUBE IN A FLOWING STARCH SOLUTION

center temperature. The predicted temperature was calculated by using  $h_p$  values that were determined by solving the reverse heat transfer problem. These are typical curves for a conduction heating material in a fluid one would expect to find. The observed and predicted temperatures are in excellent agreement.

Tables 2 and 3 show the experimentally determined particle/fluid interface convective heat transfer coefficient for starch solutions and water flowing past a silicone cube at a temperature of 129.4°C (265°F). The values ranged from 55.63 to 89.5 W/m<sup>2</sup>°C for starch solutions and from 64.67 to 107.11 W/m<sup>2</sup>°C for water. The resultant equations of the regression analysis performed on Eq. 5 are detailed below.

**Starch Solutions**  $Nu = 2.0 + 2.82 \times 10^{-3} Re^{1.16} Pr^{0.89}$  *corrected 22070.34*

$$\frac{Nu = 2.0 + 2.82 \times 10^{-2} Re^{1.6} Pr^{0.89}}{\text{coefficient of determination, } R^2 = 0.79} \tag{6}$$

1.23 ≤ Re ≤ 27.38  
 9.47 ≤ Pr ≤ 376.18

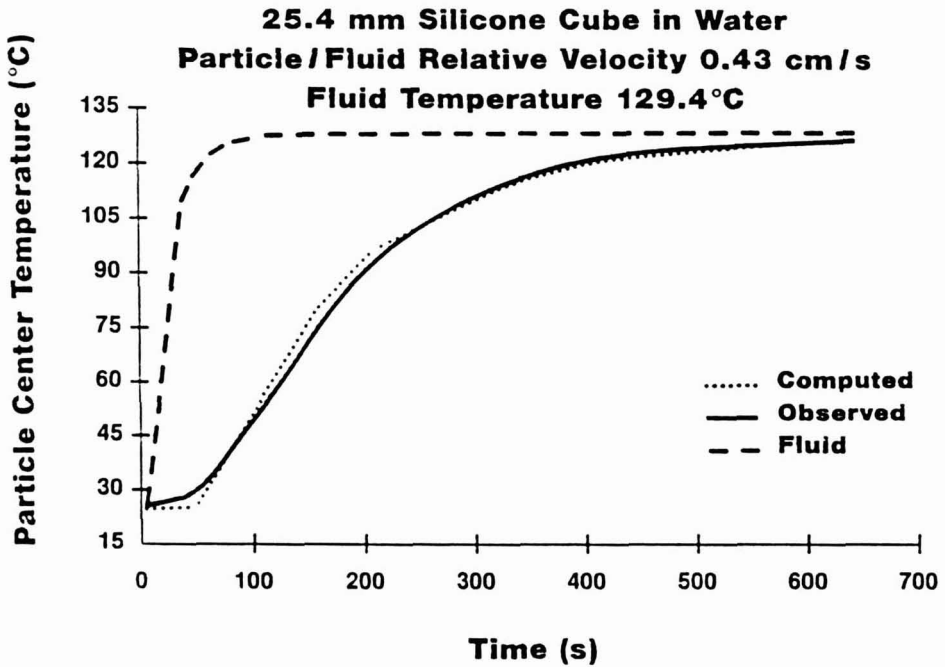


FIG. 5. TYPICAL TIME TEMPERATURE PROFILE FOR HEATING A 25.4 MM SILICONE CUBE IN FLOWING WATER

Water  $Nu = 2.0 + 1.33 \times 10^{-3} Re^{1.08}$  *Corrected 29 of 34*

$$\frac{Nu}{(\text{coefficient of determination, } R^2 = 0.89)} = 2.0 + 3.33 \times 10^{-2} Re^{1.08} \tag{7}$$

$287.29 \leq Re \leq 880.76$

The rheological properties of the starch solution shown in Table 2 were determined at 30°C; properties at the experimental temperature (129.4°C) were not available since our rotoviscometer could not be operated at 129.4°C. We are also reluctant to extrapolate rheological data from lower temperatures because the relationship between temperature and rheological parameters is very complex (Dail 1989). A simple Arrhenius type relationship does not necessarily hold for crosslinked starch solutions such as the one used in our experiments. We recognize that some error is, therefore, inherent in Eq. 6 above; however, they are conservative. The value of  $h_p$  shown in Tables 2 and 3 are real, and determined experimentally.

The magnitude of convective heat transfer coefficient at the particle/fluid interface is affected by the product of powers of Reynolds and Prandtl numbers;

TABLE 3.  
CONVECTIVE HEAT TRANSFER COEFFICIENT FOR WATER FLOWING  
PAST A 25.4 MM SILICONE CUBE

Particle/Fluid Relative Velocity	Reynolds <sup>a</sup> Number Re	Particle/Fluid <sup>b</sup> Convective Heat Trans. Coefficient		Nusselt Number Nu
		$h_p$	Std. Dev.	
cm/s		$W/m^2\text{ }^\circ\text{C}$		
0.43	287.29	64.67	2.04	2.46
0.66	471.22	83.64	4.01	3.16
0.78	519.31	85.72	2.86	3.26
0.97	672.14	89.87	3.03	3.40
1.07	747.12	95.60	2.85	3.61
1.21	880.71	107.11	3.36	4.04

<sup>a</sup>At film temperature

<sup>b</sup>Each value is a mean of seven (7)

thus, it is affected by the particle/fluid relative velocity. Actual particle/fluid relative velocity in an aseptic processing system must therefore be known. No such information can be found in the literature currently, and is difficult to determine experimentally.

Forced convection of fluids over submerged solids has been studied by several researchers (Kramers 1946; Jakob 1949; Ranz and Marshall 1952; and McAdams 1954). Our data indicate that it is possible to approach a Nusselt number of 2.0 even with fluid moving past the particle. However, Ranz and Marshall (1952) indicated 2.0 would be a minimum value for static fluids. As a matter of fact, data from Chandarana (1988) for a 25.4 mm silicone cube heated by static water at 128.3°C actually results in a Nusselt number of 1.89. Our data shows Nusselt number values lower than those reported in the literature for forced convection. As a matter of fact, our data indicates the possibility of mixed convection heat-transfer, maybe even natural convection as would be quite likely in a highly viscous product in a holding tube. Our data therefore represents the worst case situation in a holding tube. As more information about particle/fluid interaction and relative velocity in an aseptic processing system becomes available, we will be able to use more appropriate data. It is important to note at this point that as far as process calculation is concerned, knowing the value of  $h_p$  is critical; Nu values are an indirect way to obtain  $h_p$  values. In the meantime, our data can be used as initial guidelines.

The equipment, experimental procedures, and method of analysis used in this research can be adapted to any particle/fluid relative velocity. In addition, a wide variety of Newtonian and non-Newtonian fluids and types of particles can be studied.

## CONCLUSIONS

Convective heat transfer coefficients at the particle/fluid interface were determined for starch solutions and water flowing past model food particles. Values ranged between 55.63 and 89.5 W/m<sup>2</sup>°C for starch and between 64.67 and 107.11 W/m<sup>2</sup>°C for water. Flow and thermophysical parameters of fluids were related to the particle/fluid interface convective heat transfer coefficient by regression analysis. For the non-Newtonian fluid, the particle/fluid interface heat transfer coefficient was correlated to the powers of Reynolds and Prandtl numbers; for the Newtonian fluid, the particle/fluid interface heat transfer coefficient was correlated to the Reynolds number.

## ACKNOWLEDGMENT

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## NOMENCLATURE

- $C_p$  = Particle specific heat (kJ/kg°C)  
 $C_{pf}$  = Fluid specific heat (kJ/kg°C)  
 $D$  = Characteristic length (length of particle, m)  
 $h_p$  = Particle/fluid interface convective heat transfer coefficient (W/m<sup>2</sup>°C)  
 $k_f$  = Fluid thermal conductivity (W/m°C)  
 $k_p$  = Particle thermal conductivity (W/m°C)  
 $K$  = Consistency coefficient (Pa s<sup>n</sup>)  
 $\mu$  = Fluid viscosity (kg/m · s)  
 $nn$  = Number of observations  
 $n$  = Flow behavior index

$$Nu = \frac{h_p D}{k_f}$$

$$\text{Pr} = \frac{C_{pf} K \left( \frac{3n+1}{n} \right)^n 2^{n-3}}{K_f \left( \frac{D}{V} \right)^{n-1}} \quad \text{for non-Newtonian fluid}$$

$$\text{Pr} = \frac{C_{pf} \mu}{k_f} \quad \text{for Newtonian fluid}$$

$$\text{Re} = \frac{D^n v^{2-n} \rho}{8^{n-1} K \left( \frac{3n+1}{4n} \right)^n} \quad \text{for non-Newtonian fluid}$$

$$\text{Re} = \frac{\rho V D}{\mu} \quad \text{for Newtonian fluid}$$

SSSD = Standardized sum of the square of the difference between observed and calculated time/temperature data

T = Temperature of particle (°C)

T<sub>c</sub> = Calculated particle center temperature (°C)

T<sub>f</sub> = Fluid temperature (°C)

T<sub>o</sub> = Observed particle center temperature (°C)

t = time (sec.)

x, y, z = Cartesian coordinates

X, Y, Z = Particle dimensions (m)

ρ = Particle density (kg/m<sup>3</sup>)

α<sub>p</sub> = Particle thermal diffusivity (m<sup>2</sup>/s)

V = Mean fluid velocity (m/s)

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# INACTIVATION OF PROTEASES AND LIPASE IN MILK IN THIN FILM SCRAPED SURFACE HEAT EXCHANGER

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## ABSTRACT

*A cascade thin film scraped surface heat exchangers, having sterilizer, regenerator and cooler sections was designed and fabricated. It was employed for inactivation of thermostable proteases and lipases in milk. Buffalo milk was sterilized in the temperature range: 143-152°C for holding times of 0.75, 1.0 and 1.25 s. Samples collected aseptically were stored at 37°C to study the proteolytic and lypolytic activities. The study established that activity of enzymes in milk subjected to higher temperature was far less than that of milk processed at lower temperature for same holding time. The effect of longer holding times was similar.*

## INTRODUCTION

Bulk storage of chilled milk at collection centres for two days or longer and additional storage at dairy plants is becoming increasingly common. At refrigeration temperatures, the growth of psychrotrophic bacteria continues. Most enzymes formed by these psychrotrophs are heat resistant and thus are capable of degrading UHT milk.

Enzymes in milk are of two kinds: those present naturally through secretion and those which appear in milk as a result of bacterial growth. Bacterial proteases and lipases are extremely heat resistant and have a low temperature coefficient of inactivation ( $Z$ , 20 to 60°C). Their occurrence and characteristics have been reviewed by Cogan (1977), Adams (1979) and Cerf (1981). The heat resistance of these enzymes is so high that UHT process fails to inactivate them. This causes deterioration of UHT milk during storage. The degree of inactivation of these enzymes can be one useful criterion for assessing conditions of a UHT process.



Many workers observed age thickening, gelation, coagulation during storage of UHT milk. Snoeren and Evers (1978) observed proteolysis in UHT milk and attributed it to milk proteinase. Several investigators concluded that gelation is not a direct consequence of thermal treatment, but instead that it results from a biochemical process in which the indigenous milk proteinases play a leading role owing either to residual activity after treatment or reactivation during storage.

Zadow *et al.* (1975) recommended that in order to obtain longer shelf-life of UHT milk, it should be subjected to a temperature of 150°C or lower with longer holding times. Because of superior flow and residence time distribution characteristics of a thin film Scraped Surface Heat Exchanger (SSHE), it was felt that milk could be subjected to higher sterilization temperatures in such a heat exchanger for inactivation of enzymes without causing deterioration to milk quality. It was expected that accelerated cooling obtainable from SSHE would reduce the undesirable chemical changes. This paper presents an investigation on inactivation of enzymes at higher UHT temperatures by employing thin film SSHE.

## MATERIALS AND METHODS

Proteolytic activity in raw buffalo milk and UHT treated milk was measured as the increase in trichloroacetic acid soluble free amino groups and was determined colorimetrically with trinitrobenzene sulfonic acid (TNBS). Free amino groups were determined by the method of Fields (1971) as modified by Spadero *et al.* (1979). Absorbance at 420 nm was measured in spectrophotometer (Model 120, Hitachi, Japan). A standard curve was plotted between concentration of free amino groups and absorbance. Lipolytic activity was determined by extraction, titration method as described by Deeth and Fitz-Gerald (1976).

### Experimental Set-up

The experimental set-up (Fig. 1) consisted of feed tank (1), feed pumps (2,3), sterilizer (4), regenerator (5), cooler (6), liquid sealing tube (10), and aseptic sampling unit (11). The sterilizer, regenerator and cooler units were three scraped surface heat exchangers whose rotors were driven by a single motor.

Milk was first pumped to the regenerator section so as to recover heat from the sterilized milk. The temperature of raw milk leaving the regenerator was in the range of 65° to 70°C. It was raised to temperatures in the range of 143° to 152°C in the sterilizer. The holding time in the sterilizer was varied by changing the mass flow rate of milk. Holding times of 0.75, 1.0 and 1.25 s were obtained from mass flow rates of  $1.33 \times 10^{-2}$ ,  $1.67 \times 10^{-2}$  and  $2.23 \times 10^{-2}$  kg/s, respectively. Equipment was manipulated to obtain different time-temperature combinations in the range mentioned.

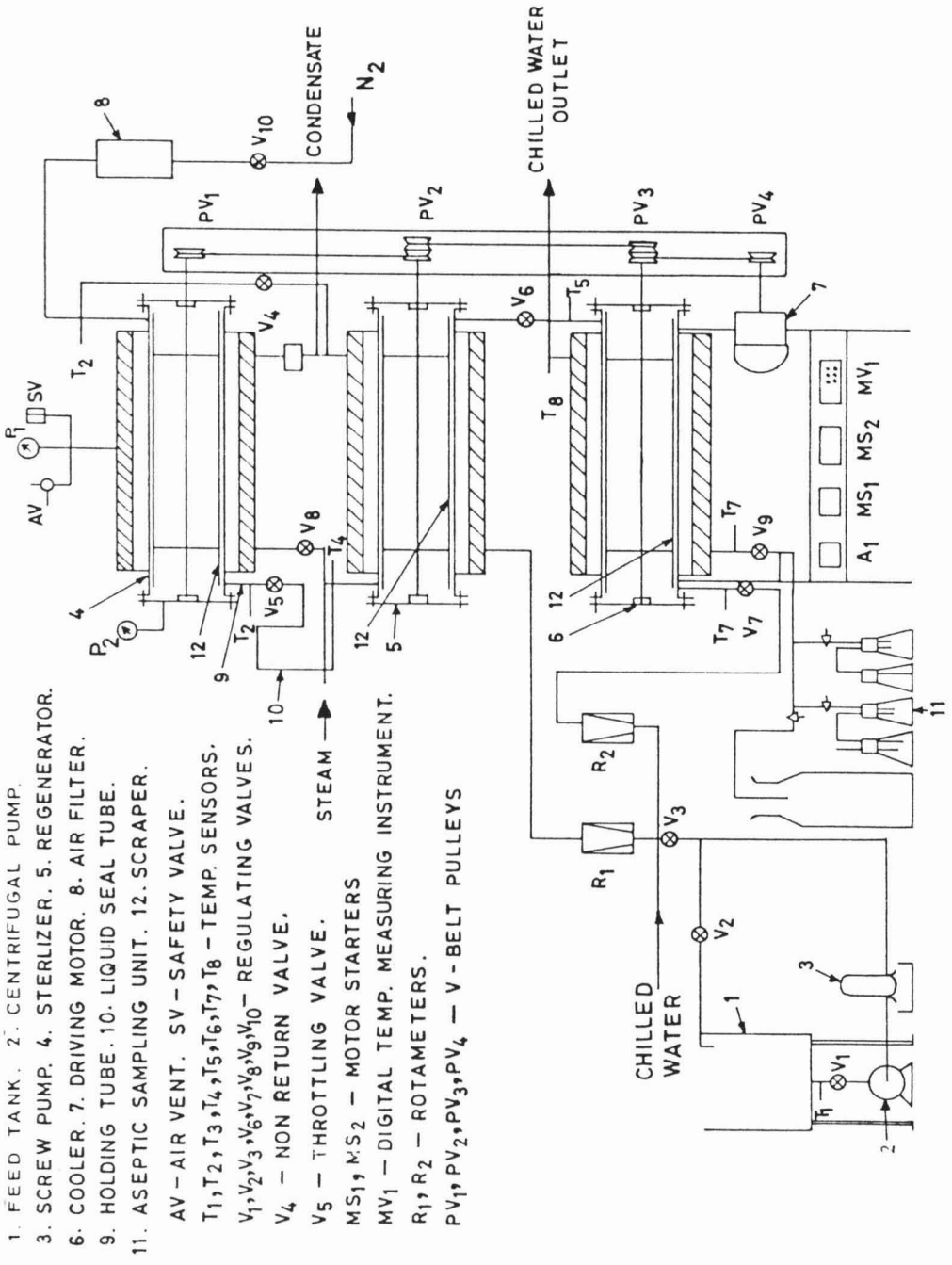


FIG. 1. SCHEMATIC DIAGRAM OF CASCADE THIN FILM SSHE

## Experimental Procedure

Raw buffalo milk collected from experimental dairy, NDRI, Karnal was stored at 7°C for a period of 4 days to increase the level of psychrotrops. The count of psychrotrops initially was  $23 \times 10^2$  (min),  $64 \times 10^4$  (max) and at the end of 4 days, it increased to  $170 \times 10^4$  (min),  $37 \times 10^6$  (max). The feed tank (1) was filled with twenty litres of stored raw buffalo milk. The pumping unit (2,3) was switched on to admit milk into the sterilizer (4). Immediately nitrogen and steam were allowed to enter into sterilizer (4) and its jacket, respectively. The motor of the rotors was switched-on. When milk appeared at the outlet of the cooler, valves ( $V_5$ ) and ( $V_{10}$ ) were regulated in such a manner that liquid seal (10) was formed at the outlet of sterilizer. The mass flow rate of milk was adjusted by regulating valves ( $V_2$ ) and ( $V_3$ ). The pressure of nitrogen in the sterilizer was also regulated to prevent boiling of milk. The chilled water was allowed to enter the jacket of cooler (6). When steady state was reached, milk was collected in aseptic sampling bottles. At the end of operation the experimental set-up was rinsed with water and then cleaned in accordance with standard procedure.

Similar trials were conducted at processing temperatures of 143, 145, 150 and 152°C for holding times of 0.75, 1.0 and 1.25 s. The samples collected were stored in an incubator at 37°C. The proteolytic activity and lipolytic activity of raw milk and stored samples were determined for storage of 0, 4, 8, 12, 16, 20 and 22 days.

## RESULTS AND DISCUSSION

Certain proteases and lipases resulting from growth of psychrotrophic bacteria are extremely heat resistant and are not inactivated by UHT process. Adams *et al.* (1975) found that proteases from psychrotrops were not inactivated even at 149°C and holding time of 10 s. From the data presented by Kessler (1981), it may be inferred that 90% proteases and lipases present in milk can be inactivated at 150°C when holding times are prolonged approximately to 45 and 120 s, respectively. For the above reasons, proteases and lipases would not be inactivated at usual UHT time-temperature combinations. Consequently, UHT processed milk would present several problems such as off-flavor, bitterness, sweet clotting, sedimentation, and gelation during storage (Jelen 1983).

When high psychrotrophic counts occur in milk, the extent of proteolysis in UHT milk during storage is monitored in terms of TNBS value. This method was selected over the Hull (1947) method, which measures the release of acid soluble tyrosine. Since proteolytic breakdown products of milk proteins frequently lack tyrosine as measured by Hull (1947) method, the TNBS test is considered as more sensitive test for detecting free amino groups even in un-

spoiled milk (Mckellar 1981). As the substrate of proteases is milk proteins, variables relating to fat percentage in UHT milk were omitted from experimental design.

Lipolytic changes in UHT milk are associated with extracellular thermostable lipases produced by the psychrotrophic bacteria. The off flavors that accompany

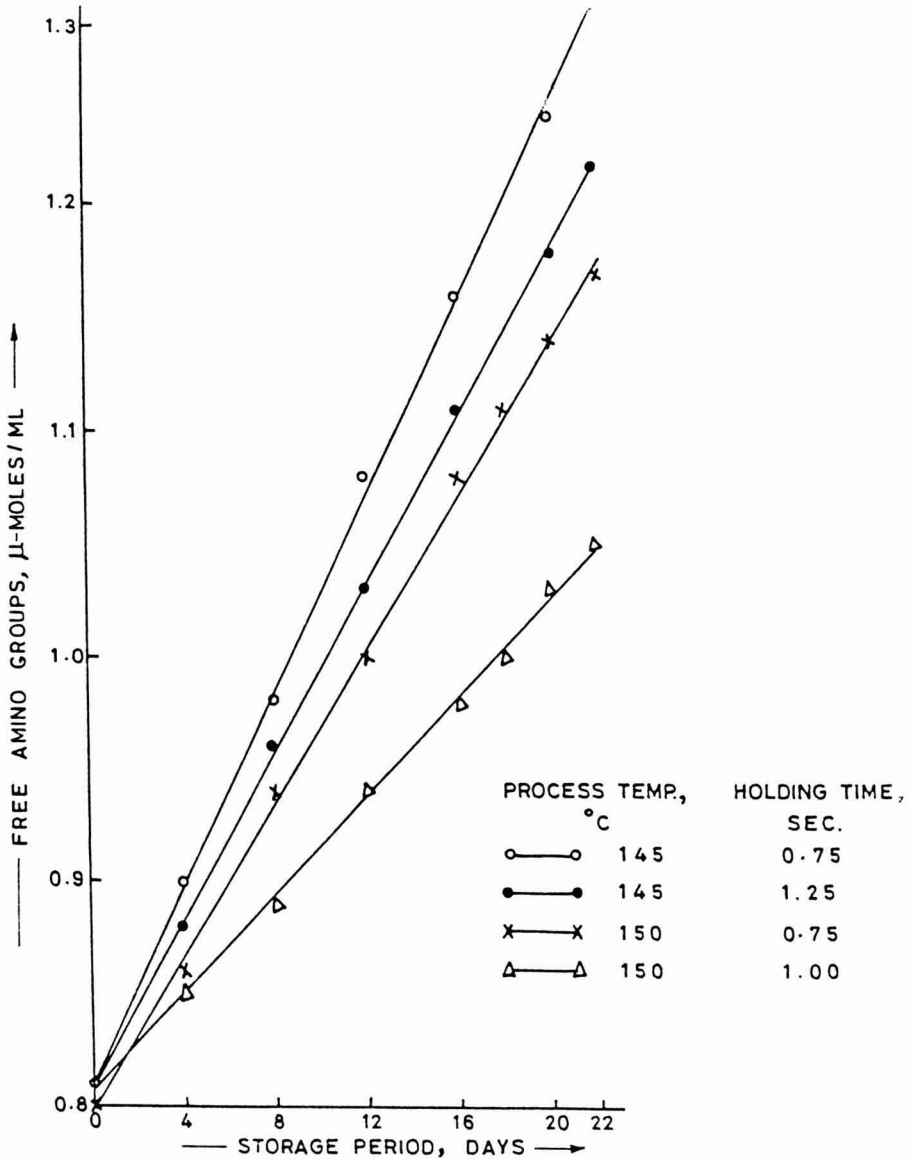


FIG. 2. EFFECT OF STORAGE PERIOD ON FREE AMINO GROUPS

breakdown of milk fat by lipases are due to free fatty acids (FFA). The lipolytic activity was measured in terms of free fatty acids.

The action of protease and lipase on milk constituents during its storage and products formed can be represented in form:

Milk proteins  $\xrightarrow{\text{Protease}}$  Fragmentation of polypeptide chain (1)

Milk triglycerides  $\xrightarrow{\text{Lipase}}$  Free fatty acids. (2)

Figures 2 to 4 indicate the cumulative concentration of above products against storage time. The rate of formation of product in enzyme mediated reactions can be written in form:

$$\frac{dP}{dt} = -k(es) \quad (3)$$

where,

$\frac{dP}{dt}$  = rate of formation of products

$k$  = a constant

$(es)$  = concentration of enzyme – substrate complex.

Since the substrate concentration (concentration of milk proteins and lipase) far exceeds the concentration of enzymes, the concentration of enzyme substrate complex can be considered constant for each time-temperature combination. For this reason, plots of Fig. 2 to 4 for each time-temperature combination show a linear relationship. It is interesting to note that in these figures, the slopes (rate of formation of product) decreases either with increasing temperature or increasing holding time for same temperature (See Table 1). This may be attributed to decrease in concentration of enzyme-substrate complex with increasing temperature or holding time. When changes in concentration of substrate are neglected due to enzymatic action, the drop in product formation rate is entirely due to the decreased enzyme concentration. This establishes that activity of enzymes in milk subjected to 152°C at 1.25 s is far less than that of milk processed at lower temperature and similar holding time.

Milk subjected to 152°C and at different holding times did not exhibit any visual defects, such as discoloration, formation of sediments, etc. during 22 days of storage.

This study has established that the performance of thin film SSHE is promising with respect to sterility and inactivation of thermostable enzymes. It has been

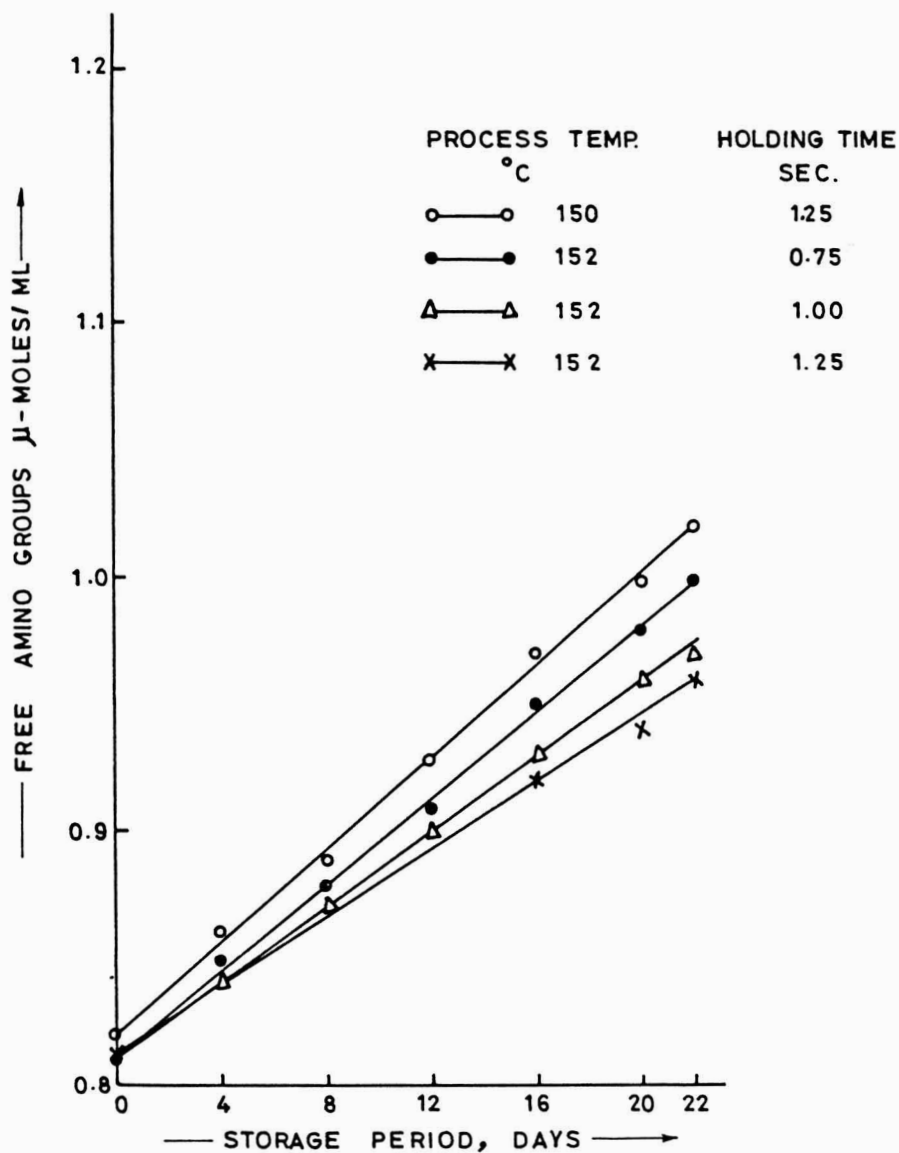


FIG. 3. EFFECT OF STORAGE PERIOD ON FREE AMINO GROUPS

reported extensively that heavy deposits are formed on the heating surface in indirect UHT systems. These deposits beside reducing heat transfer rates, cause several problems in cleaning and sanitization of the equipment. Burton (1968) reported that deposit formation extends cleaning times for UHT equipments and

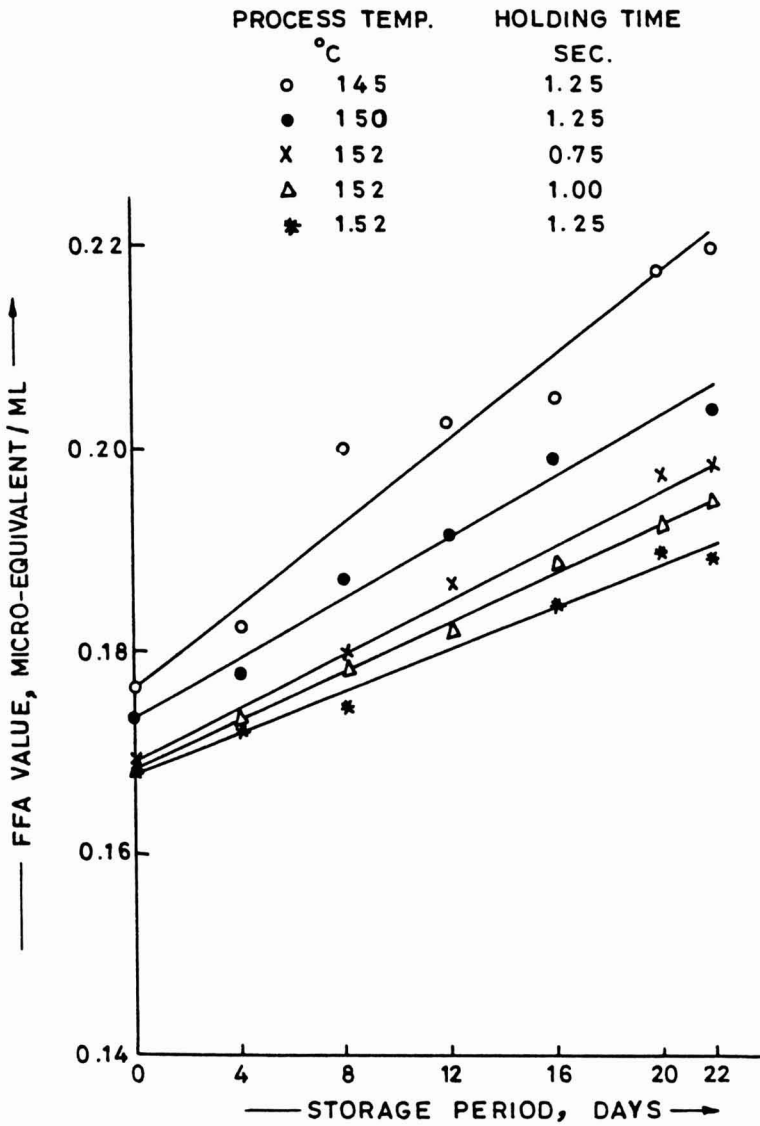


FIG. 4. EFFECT OF STORAGE PERIOD ON FFA VALUE

further necessitates several cleaning materials. These problems would be further compounded when the equipment is operated at temperature above 150°C for inactivating the thermostable enzymes. The thin film SSHE sterilizer, which minimizes the problems of deposit formation, only permits higher processing

TABLE 1.  
VARIATION IN SLOPE OF CURVES WITH HOLDING TIME AND TEMPERATURE

Process temperature °C	Holding time seconds	Slope of proteolytic activity curve	Slope of lypolytic activity curve
145	0.75	0.0225	-
145	1.00	-	-
145	1.25	0.0175	0.0025
150	0.75	0.0167	-
150	1.00	0.0100	-
150	1.25	0.0830	0.0012
152	0.75	0.0820	0.0010
152	1.00	0.0750	0.0010
152	1.25	0.0690	0.00092

temperatures for inactivation of enzymes. For these reasons, UHT processing of milk by thin film SSHE should not only result in economic operation but also give a product of longer shelf life.

## CONCLUSIONS

Thermal performance of thin film scraped surface heat exchanger was tested to inactivate the protease and lipase enzymes. The study established that activity of enzymes in milk subjected to higher temperature is far less than that of milk processed at lower temperature for same holding time. Similarly, the activity of enzymes in milk at higher holding time was less than that of lower holding time for same processing temperature.

The thin film SSHE which is free from problems of deposit formation, only permits higher processing temperatures for inactivation of enzymes. Because of mechanical limitations of experimental set-up such as stability of shaft seals, the milk could not be processed at temperatures higher than 152°C. Since the trend of results at increasing temperature for inactivation of enzymes is encouraging, it is worth extending this study beyond 152°C and subject the product for thorough evaluation of organoleptic qualities.



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# SPECIFIC HEAT OF INDIAN UNLEAVENED FLAT BREAD (CHAPATI) AT VARIOUS STAGES OF COOKING

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## ABSTRACT

*A simple inexpensive calorimeter was built to measure specific heat of foods at various process temperatures. By using vegetable/mineral oil as the heating medium in place of water, specific heat at temperatures beyond 100°C can also be evaluated. Specific heat of whole wheat dough and Chapati (round disc prepared mostly from whole wheat flour dough) at various stages of cooking and puffing were determined. Based on the experimental data a linear equation ( $C = 2476.56 + 23.56M - 3.79T_c$ ) is proposed from the experimental data for specific heat of wheat flour, dough, cooked and puffed Chapati and for other food materials at moisture levels ranging from 0.1% to 80% and temperature ranges from 303° to 336° K.*

## INTRODUCTION

*Chapati* is a round disc of 1–1.5 mm thick and 150–200 mm in diameter mostly prepared from whole wheat flour dough. After rolling, it is baked on a pan by contact heating and puffed directly on gas fired burner. It is used as a staple food in most parts of India.

To design a continuous baking and puffing oven for *Chapati*, it is necessary to know the energy requirement in the system. Specific heat is one of the thermal properties required to calculate the energy requirement. Different types of calorimeters have been used in the past depending upon the structure of the materials, and the method of mixtures has been most commonly used. Although a large amount of work has been reported for the determination of specific heat of food materials, no data are available for specific heat of whole wheat flour dough, or cooked and puffed *Chapati*.

The direct method of mixtures has been used (Wright and Porterfield 1970; Suter *et al.* 1975) for determination of specific heat for peanuts and peanut pods, hulls and kernels. For hygroscopic food materials, determination of specific heat by the direct method of mixtures poses problems due to evolution of heat of solution for soluble components present in the food materials.

A differential Scanning Calorimeter (DSC) was used for determining specific heat of flue cured tobacco (Chakraborti and Johnson 1971) and for peanut (Young and Whitaker 1973) and can be used for other food materials, but the equipment is expensive and requires careful sample preparation.

The indirect method of mixtures (Hwang and Hayakawa 1979) has been used in the present work. The calorimeter used in the experimental work was to some extent similar but simpler than the one used by Kulacki and Kennedy.

The purpose of this paper is to present a simple inexpensive and portable calorimeter that was developed to determine the specific heat of dough and chapati at various stages of cooking, but can be used for other food materials as well.

## MATERIALS AND METHODS

### Apparatus

The calorimeter was made of a block of Polyurethane foam insulation having dimensions  $200 \times 200 \times 175$  mm (Fig. 1) with a cylindrical cavity of 100 mm diameter and 125 mm in depth at the center to accommodate a 500 cc capacity glass beaker. This cylindrical cavity is fitted with a rectangular cover ( $150 \times 150$  mm) made of polyurethane foam with provision for inserting a cylindrical capsule at the center, an inlet for pouring water into the beaker and two holes with suitable packing for thermocouples. One thermocouple is to measure water temperature and the other to measure temperature between the beaker and the insulation.

The test capsule is made of copper tube of 30 mm I.D., 2 mm thick and 100 mm in height with rubber stoppers at both ends. The top stopper has a 3 mm hole for inserting the thermocouple for recording the sample temperature. All the thermocouples used in the experiment were made of copper constantan and all temperatures were recorded by a data logger at intervals of 1, 2 or 5 min according to test requirements and measured with a resolution up to  $0.1^{\circ}\text{C}$ .

### Experimental Procedure

An empty beaker was placed in the cylindrical cavity and the top was covered. The capsule access hole was also covered with a rubber cork to prevent heat loss. The 400 g of water was heated in another beaker to about  $20^{\circ}\text{C}$  higher than the experimental temperature to achieve inside calorimeter temperature equal to

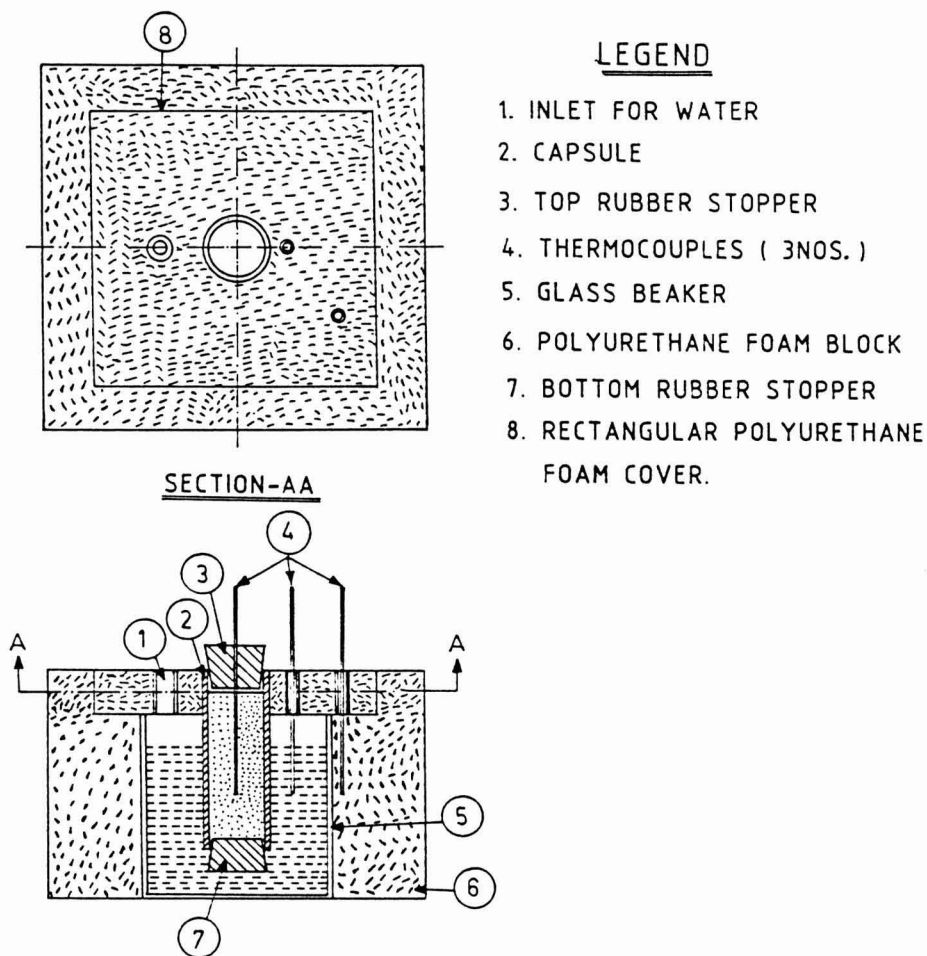


FIG. 1. SECTIONAL VIEWS OF CALORIMETER USED FOR DETERMINATION OF SPECIFIC HEAT

the experimental temperature, and transferred to the beaker in the calorimeter. The inlet for hot water was covered with a rubber cork. Once the temperature between the beaker and insulation reached  $5^{\circ}\text{C}$  higher than the experimental temperature, water from the beaker kept in the calorimeter was sucked by a rubber tube through inlet 1 as shown in Fig 1. The rubber cork from the capsule inserting hole was removed and the empty capsule with both ends was covered with rubber corks put in the beaker through the center hole. A thermocouple was inserted through the top cork to measure the temperature inside the empty

capsule. Inlet 1 was closed with a cork, later 400 g of water heated to 5°C higher than the experimental temperature was poured in the beaker. The temperature of water in the beaker, inside the capsule and between the beaker and insulation were recorded by a data logger at an interval of 1 min in the beginning and afterwards at an interval of 2 and 5 min. After a certain time (20–30 min) which depends upon the characteristics of the material, equilibrium temperature was reached i.e., the temperatures of water inside the beaker, between the beaker and insulation and inside the capsule became equal. From these data heat capacity of the calorimeter was calculated.

Capsule and water from the beaker were removed and the capsule access hole is covered with a rubber cork. To get the temperature between the beaker and the insulation equal to the experimental temperature, the above procedure was repeated. This time, the capsule was filled with a known quantity of sample material whose specific heat was to be determined. The above procedure was repeated again. While filling the capsule with sample food materials, care must be taken so that no air pockets are left inside the capsule. From these data, the specific heat of material was calculated.

**Determination of Specific Heat.** Heat capacity of the calorimeter was calculated, from energy balance and assuming that heat loss to environment was constant, from the relationship:

$$H_k = C_c W_c \frac{(T_e - T_{ic} + T_a) - C_w W_w (T_{iw} - T_e - T_a)}{(T_{ik} - T_e - T_a)}$$

Where  $H_k = C_k W_k$ , and  $T_a = dT/dt \times T_e$

$T_a$  is determined as shown in Fig. 2 and from the first set of experiments the value of  $H_k$  was calculated.

### Calculation of Specific Heat

In the second set of experiments, when the sample material was put in the capsule and the capsule was inserted in the hot water, thermal energy was released. From the law of conservation of energy, i.e., the total heat in the beginning of the system will be equal to the final heat of the system plus the heat lost to the environment, the following equation can be derived:

$$C_s = \frac{C_w W_w (T_{iw} - T_{ew} - T_a) + H_k (T_{ik} - T_e - T_a) - C_c W_c (T_e - T_{ic} + T_a)}{T_e - T_{is} + T_a}$$

The magnitude of  $T_a$  is calculated for different substances as shown in Fig. 3. Detailed calculations for heat capacity and specific heat are given in Appendix.

$$\frac{dT}{dt} \times t_e = T_a = \frac{T_e - T_2}{t_2 - t_e} \times t_e$$

$$T_a = \frac{6.6 - 6.0}{22 - 17} \times 17$$

$$= \frac{.6}{5} \times 17$$

$$T_a = 2.04 \text{ } ^\circ\text{C}$$

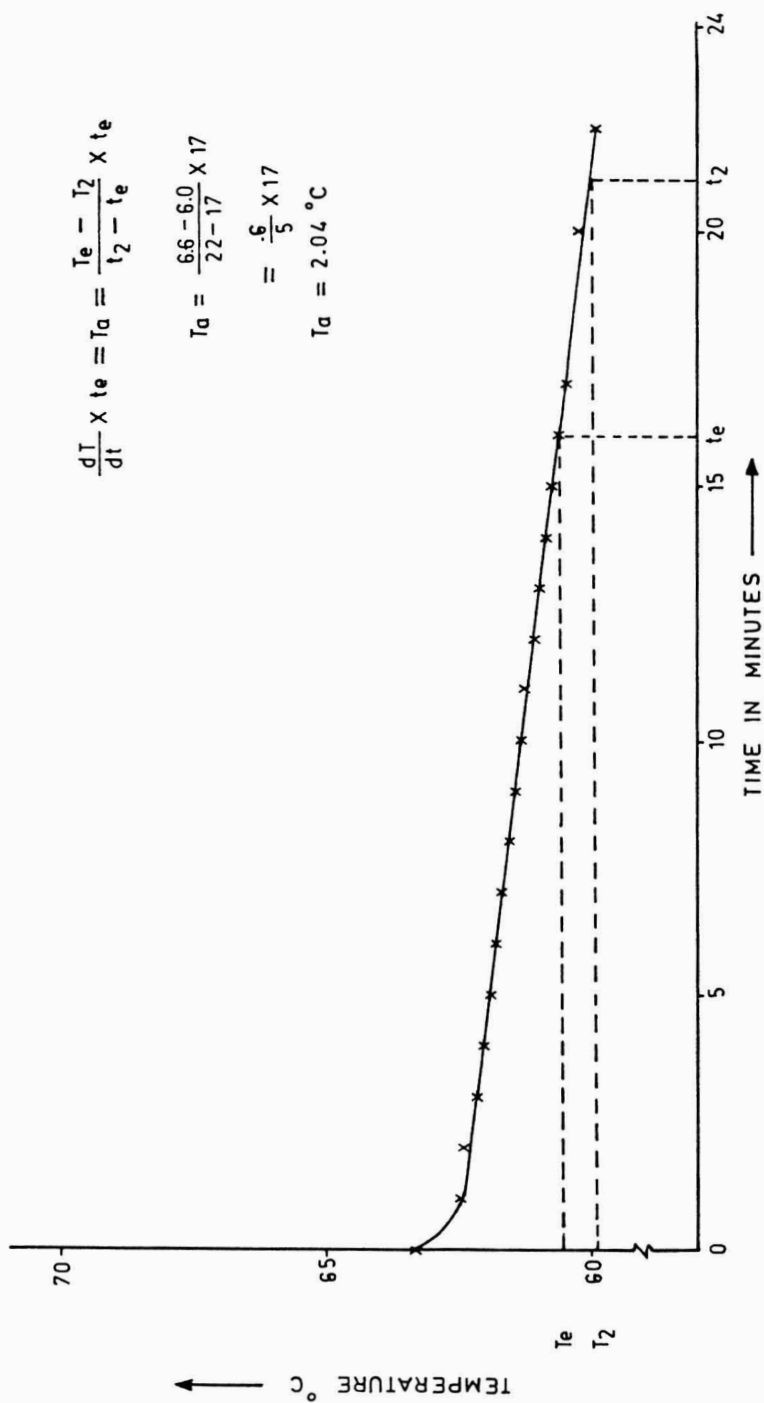
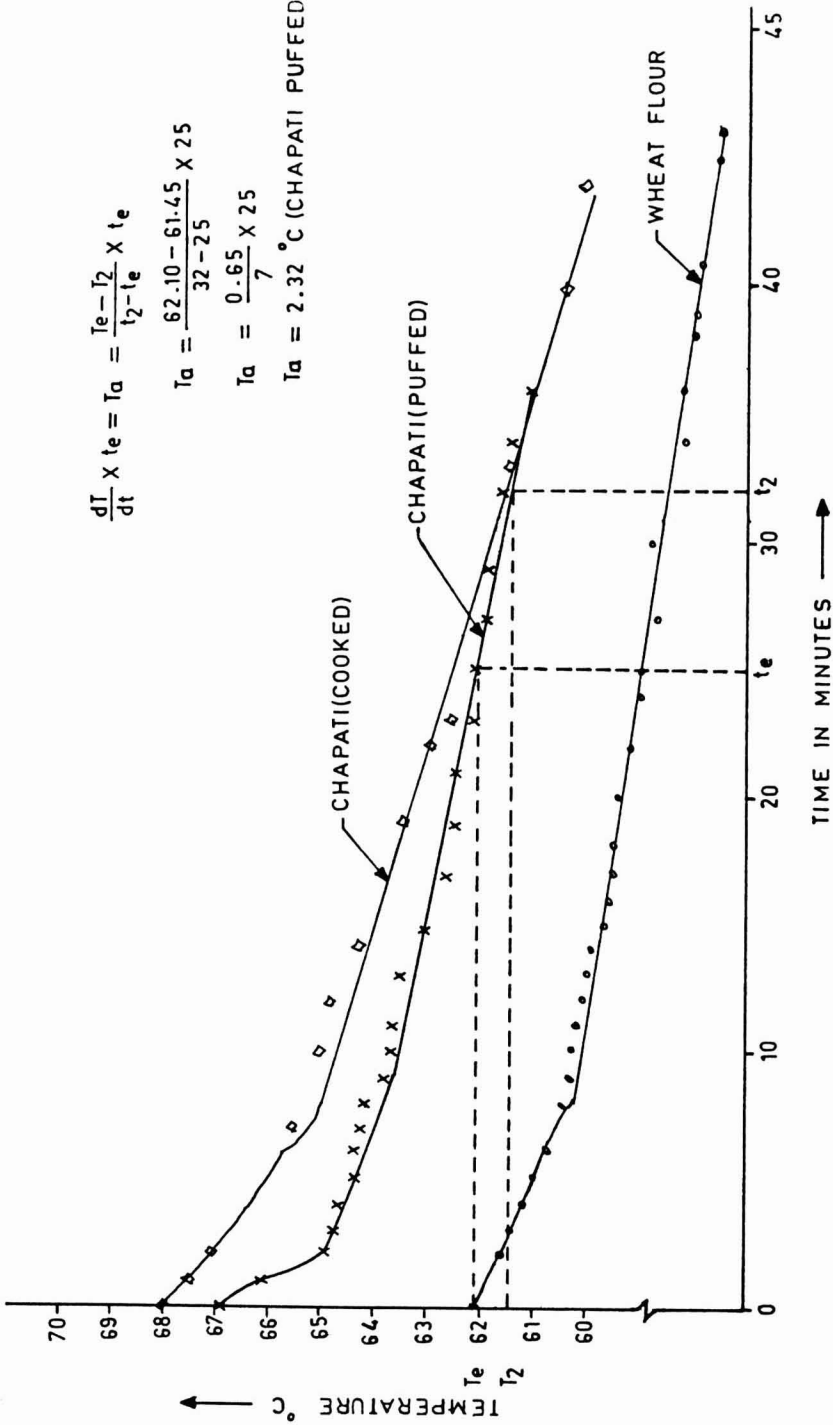


FIG. 2. DETERMINATION OF  $\frac{dT}{dt}$  FOR HEAT CAPACITY OF CALORIMETER



$$\frac{dT}{dt} \times t_e = T_a = \frac{T_e - T_2}{t_2 - t_e} \times t_e$$

$$T_a = \frac{62.10 - 61.45}{32 - 25} \times 25$$

$$T_a = \frac{0.65}{7} \times 25$$

$$T_a = 2.32 \text{ }^\circ\text{C (CHAPATI PUFFED)}$$

FIG. 3. DETERMINATION OF  $\frac{dT}{dt}$  FOR SPECIFIC HEAT OF CHAPATI (PUFFED) CHAPATI (COOKED), WHOLE WHEAT FLOUR

From a second set of experiments and by using the above equation specific heats of various substances like sugar, boiled potatoes, wheat flour, wheat dough and chapati were calculated.

## RESULTS AND DISCUSSION

Specific heat values of substances determined by the present method are reported in Table 1. Specific heat of substances whose values are well documented: sugar, boiled potatoes, whole wheat flour and wheat dough are in good agreement with those determined. The maximum deviations were 3%, 5%, 2% and 2%, respectively, with the reported values. Based on the experimental data of specific

TABLE 1.  
SPECIFIC HEAT VALUE OF SUBSTANCES DETERMINED BY PRESENT METHOD

sl. no.	Substances	Moisture content (% wet basis)	Ambient temperature °C	Wt. of material gm	$T_{iw}$ °C	$T_e$ °C	$t_e$ min	$dT/dt$ °C/min	$dT/dt \times t_e$ °C	Sp. heat values J/kg K experimental	Sp. heat values J/kg K reported (ref.5)	% deviation
1	Sugar	0.133	27	48.61	58	54.7	24.0	0.075	1.92	1297.97	1256	+3.23
		0.133	27	43.56	61.2	58.0	24.5	0.075	1.83	1272.84	,,	+1.34
		0.133	27	57.11	61.5	59.1	25.0	0.066	1.66	1256.10	,,	+0.01
2	Potatoes (boiled)	82.15	27	55.00	58.3	53.6	23.0	0.05	1.15	3517.08	3642.79	-3.45
		82.15	27	62.59	64.0	57.1	26.0	0.11	2.86	3490.00	,,	-4.19
		82.15	27	63.00	66.0	59.2	27.0	0.085	1.50	3460.45	,,	-5.00
3	Whole wheat flour	10.53	26.5	38.0	60.0	57.0	21.0	0.05	1.05	1846.30	1842.28	+0.21
		10.53	26.5	34.23	61.4	58.1	22.0	0.05	1.10	1829.70	1842.28	-0.68
		10.53	26.5	38.50	62.1	59.1	22.0	0.068	1.51	1804.59	1842.28	-2.04
										1716.67*	+7.55	
										1716.67*	+6.58	
										1716.67*	+5.12	
4	Whole wheat dough	45.37	26.5	70.42	56.7	52.0	23.0	0.075	1.72	2051.63	2009.76	+2.08
		45.37	26.5	74.13	59.5	52.1	24.0	0.160	4.00	2049.11	,,	+1.95
		45.37	26.5	84.45	68.0	62.8	26.0	0.093	1.625	2030.69	,,	+1.04
5	Chapathi (cooked)	41.16	26.5	31.57	61.1	55.3	28.0	0.100	3.00	1955.32	not available	-
		41.16	26.5	31.84	62.1	55.5	30.0	0.125	3.75	1938.58	,,	-
		41.16	26.5	40.03	68.1	61.7	31.0	0.11	3.61	1926.02	,,	-
6	Chapathi (puffed)	38.38	26.5	43.25	61.2	56.4	26.0	0.075	1.95	1905.08	,,	-
		38.38	26.5	36.46	64.2	59.1	28.0	0.075	2.10	1896.75	,,	-
		38.38	26.5	43.4	66.0	62.1	25	0.092	2.32	1889.17	,,	-
7	Heat cap. of calorimeter		26.5	-	63.3	60.7	17	0.12	2.04	heat capacity of calorimeter = 55.57 cal/deg.C		

\* (Hwang and Hayakawa 1979)



heat, the following equation was developed to estimate the specific heat of any substance with moisture in the range of 0.1% to 80% (wet basis)

$$C = 2476.56 + 23.56 M - 3.79 T_e \quad (r = 0.99)$$

Comparison of specific heat obtained by this equation with the Siebel equation i.e.,  $C = 837.4 + 33.49 M$ , and the Dickerson equation (Heldman and Singh 1981) i.e.,  $C = 1675 + 25 M$ , have been reported in Table 2.

The equation suggested in the present work gives fairly good values for substances having moisture contents ranging between 0.1 to 80% like sugar, wheat flour, starch, dry milk, rice etc., while for substances containing higher moisture (more than 80%) the present equation shows a higher deviation from reported values.

The accuracy of the experimental method depends upon the accuracy of measurement of temperature and determination of  $dT/dt$  as shown in Fig. 2 and 3.

#### *Nomenclature*

C = Specific heat of substance,	J/kg K
T = Temperature,	K
W = Weight of substance,	Kg
R = Heat lost to environment,	J
M = Percentage moisture content (wet basis)	
t = Time,	min
r = Regression coefficients	

$A_1, B_1, C_1, D_1$  and  $E_1$  = constants

#### Subscript:

- s = substance whose specific heat is to be determined
- e = equilibrium state
- c = capsule
- w = water
- i = initial
- k = calorimeter

## APPENDIX

### Determination of Specific Heat:

Heat capacity of the calorimeter was calculated as follows:

From the law of conservation of energy, the heat given up by the water and calorimeter is equal to the heat taken by the capsule plus heat lost to environment i.e.,

TABLE 2.  
COMPARISON OF PRESENT EQUATION WITH OTHER EQUATIONS FOR PREDICTION  
OF SPECIFIC HEAT

Sl. no.	Item	Moisture content (% wet basis)	Sp. heat values J/kg K above freezing point according to						
			Reported values (ref.5)	Present model	% deviation	Siebel model	% deviation	Dickerson model	% deviation
1	Sugar	0.133	1256.00	1237.71	-1.45	840	-35.28	1678	+29.27
		0.133	1256.00	1225.20	-2.45				
		0.133	1256.00	1221.04	-2.78				
2	Potatoes (boiled)	82.15	3642.78	3174.20	-12.86	3630	+3.21	3720	+5.76
		82.15	3642.78	3160.94	-13.22				
		82.15	3642.78	3152.98	-13.44				
3	Whole wheat flour	10.53	1842.28	1472.94	-19.99	1195	-33.77	1938	+3.39
		10.53	1842.28	1469.78	-20.21				
		10.53	1842.28	1465.99	-20.42				
		10.53	1716.67*	1473.94	-14.13	1195	-30.38	1938	+2.89
		10.53	1716.67*	1469.78	-14.38				
10.53	1716.67*	1465.99	-14.60						
4	Whole wheat dough	45.37	2009.76	2313.72	+15.12	2379	+15.95	2800	+36.47
		45.37	2009.76	2313.35	+15.10				
		45.37	2009.76	2272.79	+13.08				
5	Chapathi (cooked)	41.16	1926.02**	2202.03	+14.33	2236	+16.09	2704	+40.39
		41.16	1926.02**	2201.27	+14.29				
		41.16	1926.02**	2177.77	+13.07				
6	Chapathi (puffed)	38.38	1889.17**	2132.37	+12.87	2141	+13.33	2634	+39.42
		38.38	1889.17**	2122.14	+12.33				
		38.38	1889.17**	2110.77	+11.73				
7	Starch	12.0	1754	1610.91***	-8.15	1239.28	-29.34	1975	+12.59
8	Dry milk(non fat)	3.5	1520	1410.65***	-7.19	954.61	-37.19	1762.5	+15.95
9	Rice	12.0	1758.54	1610.91***	-8.39	1239.28	-29.52	1975	+12.3
10	Peas (air dried)	14.0	1842.28	1658.03***	-10.00	1306.26	-29.09	2025	+9.91
11	Figs (dried)	24.0	1632.93	1390.63***	+15.96	1641.16	+0.5	2275	+39.32
12	Yolk of egg	48.0	2805.29	2459.07***	-12.34	2444.92	-12.84	2875	+2.48
13	Fish (canned)	70.0	3350.00	2977.39***	-11.12	3181.70	-5.02	3425	+2.23
14	Honey(radish)	73.4	3262.86	3057.49***	-6.29	3295.56	+0.9	3510	+7.47
15	Dates (fresh)	78.0	3433.34	3165.87***	-7.79	3449.62	+0.47	3625	+5.5

\* According to (Hwang and Hayakawa 1979)

\*\* Experimental values obtained in the present work have been taken, as no reported values are available

\*\*\* Specific heat values have been calculated at  $T_e = 303^{\circ}\text{K}$

$$C_w W_w (T_{iw} - T_e) + C_k W_k (T_{ik} - T_e) = C_c W_c (T_e - T_{ic}) + R \quad (1)$$

It is assumed that heat lost to environment is constant

$$R = dT/dt (C_w W_w + C_k W_k + C_c W_c) t_e \quad (2)$$

$$\text{Let } C_k W_k = H_k$$

$$\text{(heat capacity of calorimeter)} \quad \left. \begin{array}{l} \\ \\ \end{array} \right\} \quad (3)$$

$$\text{and } dT/dt \times t_e = T_a$$

Putting the values of R,  $H_k$  and  $T_a$  from Eq. (2) and (3) respectively, in (1)

$$H_k = C_c W_c \frac{(T_e - T_{ic} + T_a) - C_w W_w (T_{iw} - T_e - T_a)}{(T_{ik} - T_e - T_a)} \quad (4)$$

$T_a$  is determined as shown in Fig. 2 and from the first set of experiments the value of  $H_k$  was calculated.

### Calculation of Specific Heat

In the second set of experiments, when the sample material was put in the capsule and the capsule was inserted in the hot water, thermal energy was released. From the law of conservation of energy, i.e., the total heat in the beginning of the system will be equal to the final heat of the system plus the heat lost to the environment i.e.,

$$C_w W_w (T_{iw} - T_e) + H_k (T_{ik} - T_e) = C_c W_c (T_e - T_{ic}) + C_s W_s (T_e - T_{is}) + R \quad (5)$$

where the heat lost to the environment is given by

$$\begin{aligned} R &= dT/dt (C_w W_w + H_k + C_c W_c + C_s W_s) t_e \\ &= (C_w W_w + H_k + C_c W_c + C_s W_s) T_a \end{aligned} \quad (6)$$

Putting the value of R from Eq. (6) into Eq. (5)

$$C_s = \frac{C_w W_w (T_{iw} - T_{ew} - T_a) + H_k (T_{ik} - T_e - T_a) - C_c W_c (T_e - T_{ic} + T_a)}{T_e - T_{is} + T_a} \quad (7)$$

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# QUALITY OF ARTIFICIALLY DRIED LENTIL

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## ABSTRACT

*The effects of artificial drying on Laird lentil qualities such as breakage susceptibility, cooking quality, and seed germination were determined at three initial moisture levels, 16%, 18%, 20% wet basis and seven levels of drying temperature varying from 40°C to 80°C. Cooking quality was not affected by drying in the range of treatments used in this study. High initial moisture content and lengthy drying periods at temperatures above 40°C were associated with increased seed breakage. Seed germination was particularly sensitive to heat treatment at 80°C and extended drying time for high moisture samples.*

## INTRODUCTION

Grain lentil (*Lens culinaris* M.) is a high-protein pulse crop grown mainly for human consumption. The composition of Canadian-grown lentil averages, on a dry basis, 28.6% protein, 3.1% ash, 4.4% crude fiber, 0.7% ether extract, and 63.2% Nitrogen-free extract (Bhatty 1988).

Two lentil cultivars are registered in Canada. The large-seeded Laird which is the most popular cultivar (75% of the total production) and the small-seeded

Eston. Lentil plants have an indeterminate growth habit, and at harvest, plants may contain immature pods as well as over-ripe pods which shatter readily. In order to reduce shattering losses, the crop is usually swathed when the earliest pods have turned light brown. After about a week of maturing and drying, the swaths are threshed. The optimum moisture content for threshing is 18–20% to minimize mechanical damage to the seeds. The harvested seeds are then artificially dried to below 14% moisture content for safe storage.

Physical damage to lentil seeds during drying and handling could be serious and is a major concern of farmers, grain merchants, and processors. The Canadian grain grading system (Canadian Grain Commission, 1987) specifies that for Canada No. 1 and No. 2 lentils, split and broken seeds must be less than 2.0% and 3.5%, respectively.

Artificial drying at excessively high temperature reduces seed germination. Canadian Seed Regulations (Anonymous 1987) specify minimum germination rates of 85% and 75% for No. 1 and No. 2 lentil seed, respectively. In the absence of experimental information, a maximum temperature of 43°C has been recommended for drying lentil seeds (Slinkard *et al.* 1988), based on research results with other legumes.

The effect of high temperature drying on cooking quality of lentils is unknown.

The objective of this study was to determine the effect of specific drying regimes on lentil seed qualities as measured by the susceptibility to mechanical damage, germination and cooking quality.

## MATERIALS AND METHODS

### Experimental Design

To evaluate the effect of drying condition on lentil qualities, an experiment of three by seven factorial design was conducted. There were three initial moisture levels, 16, 18, 20%, and seven temperature levels, 40, 45, 50, 55, 60, 70, 80°C. To eliminate the variation in susceptibility to breakage due to differences in moisture content, all samples were dried to a uniform moisture content of  $13.4 \pm 0.2\%$  for quality evaluations.

### Sample Preparation

Certified No. 1 Laird lentil seeds were obtained from a commercial seed farm near Saskatoon, with an initial moisture content of 13.4%. Three 6-kg samples were moistened to 20, 18 and 16%. This was accomplished by placing the seeds in a controlled humid environment (about 22°C and 90% relative humidity) until the desired moisture level had been reached. The seeds were then mixed and sealed in polyethylene bags and stored at 4°C for a week so that moisture was

in equilibrium within each sample. Lentil samples at each moisture content were sieved with a 4.76 mm round hole sieve, and the overs were divided into 7 to 8 lots of about 700 g which were placed in air-tight polyethylene bags at room temperature (about 20°C) for 12 h prior to artificial drying.

Drying of lentil seeds was accomplished in a laboratory thin-layer dryer which provided stable drying conditions with drying air of 12% relative humidity and at one of seven temperatures. The hot air was forced across the thin layer sample on a screen at a constant speed. The air speed approaching the screen was measured at 0.3 m/s. Variation in moisture content of the sample during the drying process was monitored with the sample holder suspended from an electronic balance. Lentils were removed from the dryer when the moisture content reached  $13.4 \pm 0.2\%$ , and immediately sealed in plastic bags. The dried samples were stored at room temperature for about a week before the quality evaluations.

### **Breakage Testing**

To measure the susceptibility of lentil seeds to breakage, the Stein Breakage Tester Model CK-2M (Stein Laboratories, Kansas) was used. This equipment consists of a cylindrical cup, 92 mm in diameter and 90 mm in height, and a two-blade impeller rotating at 1725 rpm inside the cup. The impeller is controlled by a timer which can be set at 1 to 5 min. Samples of 100 g, retained on a 4.76 mm round hole sieve, were placed in the cup and were subjected to abrasively impact by the impeller for 4 min. The samples were removed and sieved again with the 4.76 mm round hole sieve for 40 strokes. The overs were weighed. The difference between the weight of the original sample and of overs was used to calculate percent of breakage which was then used as the index of the susceptibility to breakage.

Three replications of breakage testing were made while the order of the tests was randomized.

### **Cooking Quality**

Cooking quality of lentil was evaluated using the method developed by Bhatti *et al.* (1984). Lentil samples (about 10 g dry weight) were added to 50 mL of distilled and deionized water in a 250 mL Erlenmeyer flask covered with tin foil. The flasks were then immersed and held in a bath of boiling water for 60 min. The water was drained off on a fine sieve, and the samples were cooled to room temperature. The texture of the sample was measured with a Kramer shear press (Model TP-1, Food Technology Corporation, Reston, VA) fitted with a TG-300 ring and a thin multi-blade shear compression cell. The maximum compression-shear force, expressed as kg/g, was used as the index of cooking quality. Three replications (cooking and shear) were used.



## Germination

The germination of the treated seeds was assessed, in four replications of 50 seeds. The tests were carried out at the Agriculture Canada Seed Testing Laboratory in Saskatoon.

Preliminary germination tests were also performed to examine if there were any difference between the tolerance to high temperature of Laird lentil and those of other crops, such as pea and wheat. Samples of certified No. 1 pea (Trapper), wheat (Katepwa), and lentil (Laird) seeds were conditioned to 20% moisture content in a humid environment condition. These samples were stored in air-tight polyethylene bags for about a week, and then dried in a thin layer laboratory dryer at each of the three temperatures, 39, 51, 66°C for the length of period listed in Table 2.

## Seed Moisture Content

Whole lentil seed samples were dried for 20 h at 130°C in an air-oven, and the moisture contents were determined as recommended in the ASAE Standard S352.1 (1989). Exploratory tests with naturally moist seeds at moisture contents ranging from 8% to 19% indicated that the moisture contents obtained at 130°C for 20 h differed from that obtained with AACC Method 44-15A (AACC, 1983) by less than 0.2%.

# RESULTS AND DISCUSSION

## Susceptibility to Breakage

Preliminary tests were conducted with naturally moist lentil seeds to examine the effect of moisture content on breakage susceptibility of Laird lentils. Six lentil samples at moisture contents varying from 8.2 to 18.6% (wb) were obtained from the swathed lentils on a commercial farm. The test results are presented in Fig. 1. Moisture content had a significant effect on the percent breakage of the seeds. Little breakage occurred when the moisture content was about 19%. Breakage increased to 5% as the seed moisture content dropped to 15% and increased sharply to 37% as the seed moisture content decreased to about 8%.

Lentil samples at three initial moisture contents 16%, 18% and 20% were dried at different temperatures to a uniform final moisture content of  $13.4\% \pm 0.2\%$ . Table 1 summarizes the results of breakage tests on artificially dried lentil samples. Increased drying temperature did not increase the percentage of breakage ( $P < 0.01$ ). In fact, a higher percentage of breakage was associated with lower drying temperature (Fig. 2), which may be attributed to a corresponding longer drying period. High initial moisture content of lentil seeds

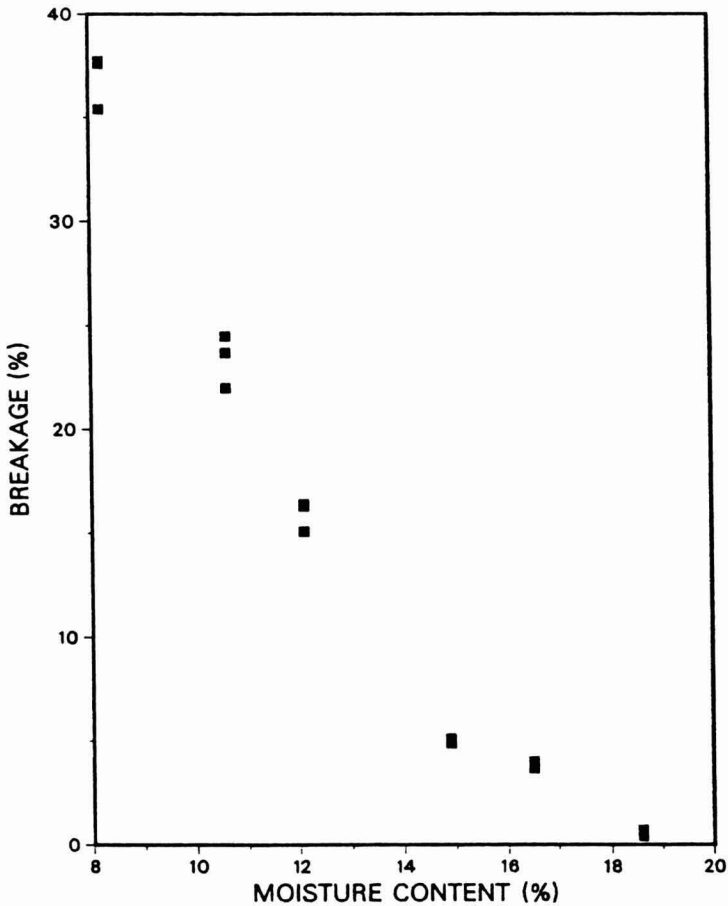


FIG. 1. EFFECT OF MOISTURE CONTENT OF LENTILS ON PERCENTAGE OF BREAKAGE IN A STEIN BREAKAGE TESTER (4 MIN)  
Three replicates.

resulted in higher percent breakage ( $P < 0.01$ ). The interaction ( $P < 0.01$ ) between drying temperature and the initial moisture content resulted in larger negative slope for the linear relationship between breakage and drying temperature for higher initial moisture content (Fig. 2). Breakage increased with increased length of drying time (Fig. 3) for 18 and 20% mc lentils. The effect of drying time on the sample with 16% initial moisture content was not significant ( $P > 0.1$ ). The interaction between drying time and initial moisture content was also not significant ( $P > 0.1$ ).

It, therefore, appeared that in the temperature range from 40 to 80°C, long drying period and high initial moisture favoured high breakage susceptibilities.

TABLE 1.  
EFFECT OF DRYING TEMPERATURE AND INITIAL MOISTURE CONTENT ON  
PERCENTAGE OF SEED BREAKAGE, TESTED IN A STEIN BREAKAGE TESTER  
(4 MIN, 3 REPLICATES)

Initial moisture content (%)	Percent breakage						
	Drying temperature (°C)						
	40	45	50	55	60	70	80
16	24.0	23.5	25.8	23.3	26.2	23.2	22.7
SD	1.4	1.2	1.0	2.5	2.1	0.7	1.2
18	32.2	31.3	32.2	29.0	31.1	29.1	27.6
SD	1.7	0.4	1.4	1.4	0.5	1.6	2.5
20	35.9	38.2	34.1	37.5	32.9	33.4	29.8
SD	0.8	0.4	1.5	0.5	2.4	1.4	0.3

### Cooking Quality

Figure 4 summarizes data for cooking quality (kg force per gram of sample) versus drying temperature. The maximum compression-shear force, for all the samples, varied from 2.9 to 3.7 kg/g with a mean of 3.4 kg/g, and c.v. of 3.6%. Bhatti *et al.* (1983) considered values less than 4.0 kg/g, to indicate fully-cooked lentils. The lentil samples treated in the present study were, therefore, well cooked. Statistical analysis of the test results showed that the effects of both drying temperature and initial moisture content on cooking quality as shown by Kramer shear press were not significant ( $P>0.1$ ).

### Germination

The germination results (Table 2) indicated that lentil samples were much less heat tolerant than the other two crops (pea and wheat). Lentil seeds suffered serious loss in germination due to artificial drying, losing 9% after being dried for 13 h at 39°C, dropping to seed grade No. 2 after 8 h drying at 51°C, and below No. 2 at 66°C after 6 h drying.

Percent germination of the dried samples in the three by seven factorial experiment is presented in Table 3. The statistical analysis of experiment results indicated no significant ( $P>0.1$ ) effect of the initial moisture content and insignificant ( $P>0.05$ ) interaction between initial moisture content and the drying temperature, when the drying temperature was lower than 70°C. The effect of drying temperature was significant ( $P<0.02$ ), and high drying temperature resulted in lower percent of germination. However, the dried samples could still make grade No. 1 lentils (Table 3). Samples dried at 80°C suffered almost total loss in germination, though they were dried for relatively short periods of time (from 18 min for 16% initial moisture content sample to 35 min for 20% one).

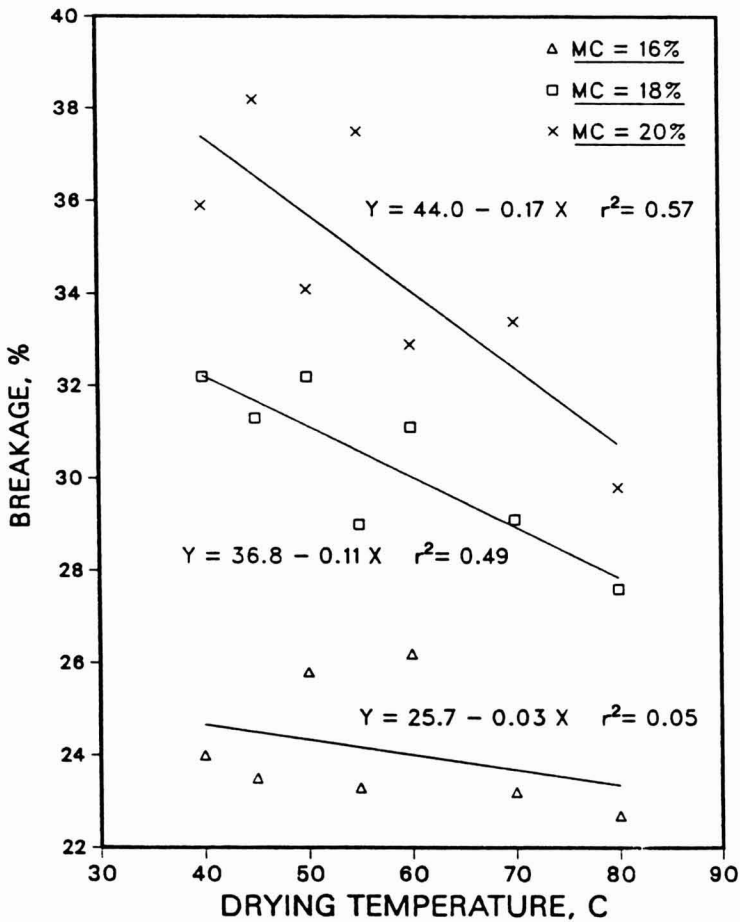


FIG. 2. EFFECT OF DRYING TEMPERATURE AND INITIAL MOISTURE CONTENT (MC) OF LENTILS ON PERCENTAGE OF BREAKAGE IN A STEIN BREAKAGE TESTER (4 MIN)

Sample moisture content 13.4%. Average of three replicates.

The tolerable germination losses for the samples dried at temperatures below 70°C in the factorial experiment showed a contrast to the much higher germination losses observed in the preliminary germination tests (Table 2), though these samples were all originally from the same batch of lentil and treated in a similar way. It should be noticed that the samples in the three by seven factorial design were dried for much shorter period (from 18 to 170 min) than those in the preliminary tests (from 360 to 780 min). A comparison of the experimental results of both tests (Table 2 and Table 3) shows that a combination of high temperatures with extended drying periods were mostly responsible for dramatic

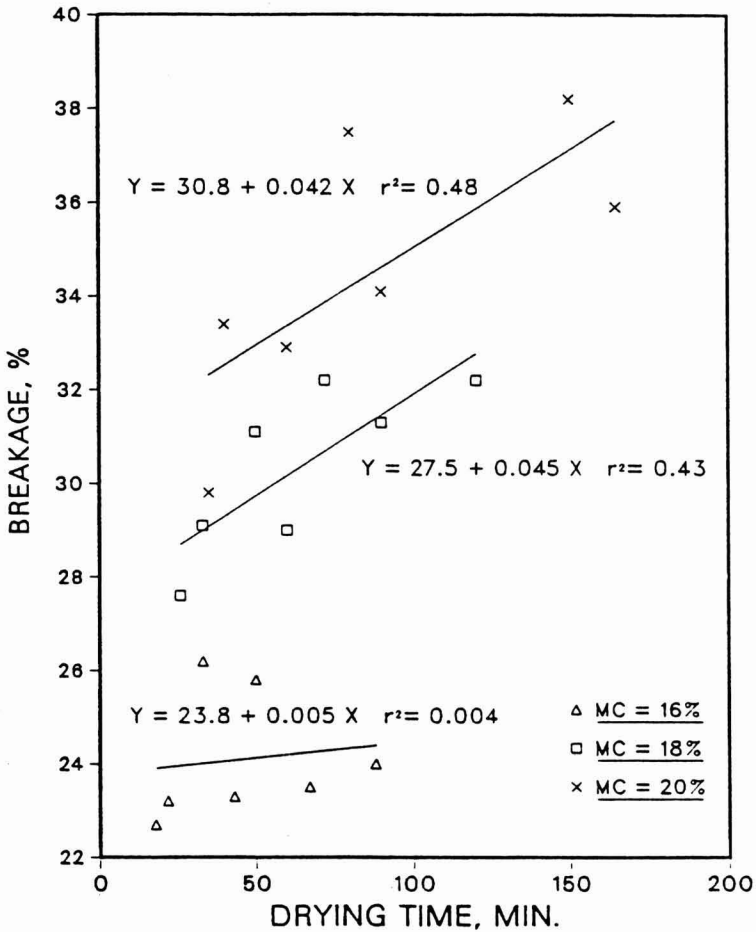


FIG. 3. EFFECT OF INITIAL MOISTURE CONTENT (MC) AND DURATION OF DRYING ON PERCENTAGE OF SEED BREAKAGE IN A STEIN BREAKAGE TESTER  
Seed moisture content 13.4%. Average of three replicates.

germination losses in lentil seeds. Experiments are planned to further examine the effect of drying condition on seed germination.

## CONCLUSIONS

- (1) Lentil seeds are susceptible to excessive breakage at moisture contents less than 15%.
- (2) The initial moisture content and the duration of drying are two major factors affecting susceptibility to breakage.

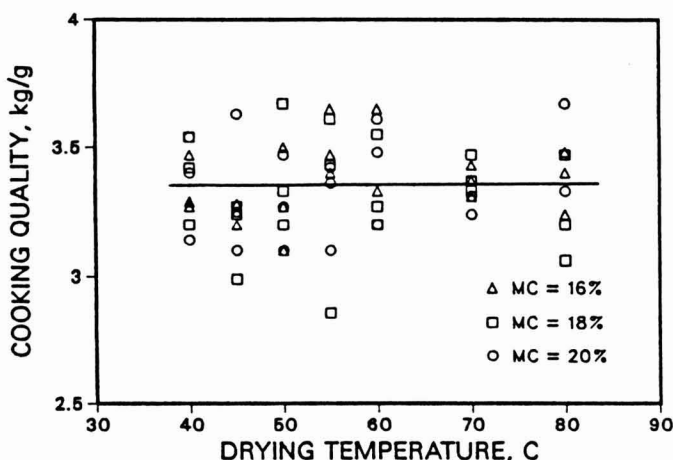


FIG. 4. EFFECT OF DRYING TEMPERATURE AND INITIAL MOISTURE CONTENT ON COOKING QUALITY OF LAIRD LENTILS  
Seed moisture content 13.4%. Three replicates.

- (3) Cooking quality of lentils is not affected by the drying temperature according to the existing criteria.
- (4) Germination loss of lentil seeds due to high temperature drying was much higher than peas and wheat dried at the same condition.
- (5) Germination was mostly influenced by drying at 80°C, and therefore drying seeds at temperatures of more than 70°C is not recommended.
- (6) The effect of relative humidity on seed quality was not studied, and more work is needed to reaffirm some conclusions drawn from this study.

TABLE 2.  
EFFECT OF INTENSITY AND DURATION OF DRYING TEMPERATURE ON PERCENT GERMINATION OF LENTIL, PEA AND WHEAT

Crop	Germination (%)				
	Control	Moistened to 20% wb	39°C 13 h	51°C 8 h	66°C 6 h
Lentil	96	96	87	78	70
SD	4.5	0.0	1.0	11	4.7
Pea	98	96	97	96	98
SD	2.3	1.9	2.6	2.0	1.9
Wheat	98	96	97	99	97
SD	0.7	2.1	2.8	0.7	2.1

TABLE 3.  
EFFECT OF DRYING TEMPERATURE AND INITIAL MOISTURE CONTENT ON GERMINATION RATE (%) OF LAIRD LENTIL SEEDS (4 REPLICATES OF 50 SEEDS)

Initial moisture content (%)	Germination (%)						
	Drying temperature (°C)						
	40	45	50	55	60	70	80
16	95.5	95.5	93.5	93.0	94.0	96.0	18.0
SD	3.0	1.9	1.9	2.6	1.6	2.3	5.9
18	97.0	95.0	96.5	94.5	93.5	92.5	2.5
SD	1.2	1.2	4.7	3.0	3.0	2.5	1.9
20	97.5	92.5	95.0	94.0	94.0	89.0	1.5
SD	1.0	2.5	3.5	2.8	3.7	3.5	0.9

### ACKNOWLEDGMENT

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# LIQUID-TO-PARTICLE HEAT TRANSFER DURING CONTINUOUS TUBE FLOW: INFLUENCE OF FLOW RATE AND PARTICLE TO TUBE DIAMETER RATIO<sup>1</sup>

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## ABSTRACT

*Liquid-to-particle convective heat transfer coefficients were measured during continuous flow through tubes, using an experimental technique in which a thermocouple was moved at the same speed as the particle. Water was used as the carrier fluid and transducer particles were made hollow to approximate densities of real food particles. Results from over 250 experimental runs over a fluid Reynolds number range from 7300 to 43600, showed that the convective coefficient was increased significantly with increasing fluid flow rate and particle to tube diameter ratio. Convective coefficient values ranged from 688 to 3005 w/m<sup>2</sup>°C depending on the experimental conditions. Dimensionless correlations obtained between the Nusselt number, particle Reynolds number, particle to tube diameter ratio, and the particle Froude number yielded R<sup>2</sup> values ranging from 0.82 to 0.92 depending on the complexity of the relation.*

## INTRODUCTION

Recent and ongoing interest in the aseptic processing of particulate foods has resulted in the need to measure fluid-to-particle convective heat transfer coefficients ( $h_{fp}$ ) during continuous flow. The literature on modeling of heat transfer in continuous flow systems (Sastry 1986; Lee and Singh 1988; Chandarana and Gavin 1989; Larkin 1989) have indicated that  $h_{fp}$  has significant effects on holding tube sizing if it falls in a low range, but the effect levels off beyond a certain value of  $h_{fp}$  (500 w/m<sup>2</sup>°C, according to Lee and Singh 1988). Thus, it is important

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from the standpoint of process design to characterize  $h_{fp}$  values and the parameters influencing them.

The main difficulty in measurement of  $h_{fp}$  is noninvasive monitoring of particle temperatures during continuous flow. A number of attempts have been made to measure convective coefficients between a stationary particle and moving fluid (Chau and Snyder 1988; Chandarana *et al.* 1988, 1989; Chang and Toledo 1989; Zuritz *et al.* 1990); and natural convection between a stationary particle and fluid (Chau and Snyder 1988; Alhamdan *et al.* 1990; Alhamdan and Sastry 1990). While data from these studies show agreement in some cases, valid comparison is not possible due to widely differing experimental conditions. While these studies are useful in estimating the lower bounds of  $h_{fp}$ , studies need to be conducted under conditions that closely simulate flow conditions within realistic systems.

Few studies have been conducted using moving particles. These include the works of Heppell (1985), using *B. Stearothermophilus* spores immobilized in alginic beads, Sastry *et al.* (1989), using a moving thermocouple, and Stoforos *et al.* (1989), using a liquid-crystal coated particle. These studies have indicated that  $h_{fp}$  values may be significantly higher than would be expected by natural convection alone. However, further research is necessary to validate these studies, and to accurately delineate the factors influencing  $h_{fp}$  in aseptic systems.

The objectives of the present study were (1) to measure  $h_{fp}$  values for moving particles in continuous tube flow with water as the carrier, using flow rates, particle sizes and tube diameters representative of commercial aseptic process systems; and (2) to study the effects of fluid flow rate and particle to tube diameter ratio on  $h_{fp}$ .

## MATERIALS AND METHODS

### Experimental Setup and Procedures

The experimental setup and approach used was essentially similar to that reported by Sastry *et al.* (1989). That study involved introduction of a transducer particle into a moving fluid stream, and monitoring the temperature of the particle as noninvasively as possible, using a thermocouple that was withdrawn from the downstream end at the same speed (as determined from preliminary experiments) as that of the particle. By this method, the velocity of a free particle in tube flow could be duplicated while measuring its temperature. While details of the experimental techniques are given in the above mentioned paper, the following modifications were introduced for improvement of reproducibility of particle movement, and convenience in experimentation.

(1) Use of a motor-driven setup at the downstream end of the tube to withdraw the thermocouple at the predetermined velocity. This resulted in consistently

reproducible thermocouple velocities, eliminating the variability of the manual withdrawal approach of Sastry *et al.* (1989).

- (2) Location of motor controls at the upstream end to enable a single operator to introduce the particle into the inlet port and control thermocouple withdrawal rate. (This eliminated the need for a second individual for thermocouple withdrawal at the downstream end.)
- (3) Use of a magnetic flowmeter, rather than a rotameter to measure fluid flow rate.
- (4) Use of an array of photosensors (rather than a single one) at upstream and downstream locations to sense the passage of the particle, so that the occurrence of "misses" was minimized when using the larger tube diameter.

A diagram of the modified experimental setup is shown in Fig. 1.

Because of the relatively short holding tube length that had to be used in this experiment, it was necessary to use particles that provided rapid thermal response, while possessing densities similar to that of real food particles. This was accomplished by using various hollow metallic spheres (made by joining aluminum or brass hemispheres), whose weights were adjusted to achieve the desired apparent densities. Sample densities were determined from the sample weight (accurate to the nearest 0.1 mg) and volume (calculated from diameter measurements by micrometer, correct to the nearest 0.1 mm). Correction for thermocouple mass was done by weighing each sample prior to disassembly, with the thermocouple wire removed, but the junction intact. Details of particle sizes and their properties are shown in Table 1.

### Experimental Conditions/Variations

Experiments were carried out using two tube diameters (0.0381 and 0.0508 m, corresponding to 1.5 and 2.0 in.); three particle sizes (0.0133, 0.0168 and 0.0239 m, corresponding to 0.523, 0.661 and 0.941 in.) and five flow rates (0.000133, 0.000266, 0.000465, 0.000665 and 0.000798 m<sup>3</sup>/s, corresponding to 2.1, 4.2, 7.4, 10.5 and 12.7 gpm) for each particle/tube diameter combination. All tests were conducted at atmospheric pressure, with water temperature being 45°C with  $\pm 2^\circ\text{C}$  variation between runs. In practice, not all experiments could be successfully executed, and in some cases variations from the above conditions occurred for the following reasons.

**Problems in Duplication of Particle Velocities.** At the low flow rates for the 0.0133 m particle and 0.0508 m tube, free particle velocities were too low to be duplicated successfully with thermocouple attached. At the lowest flow rate, successful duplication was possible only for the 0.0239 m particle, 0.0381 m tube. Thus, not all flow rates could be studied for every d/D ratio.

**Thermocouple Breakage and Repair.** During experiments, thermocouple wire breakage would occasionally occur. Since thermocouple junctions were

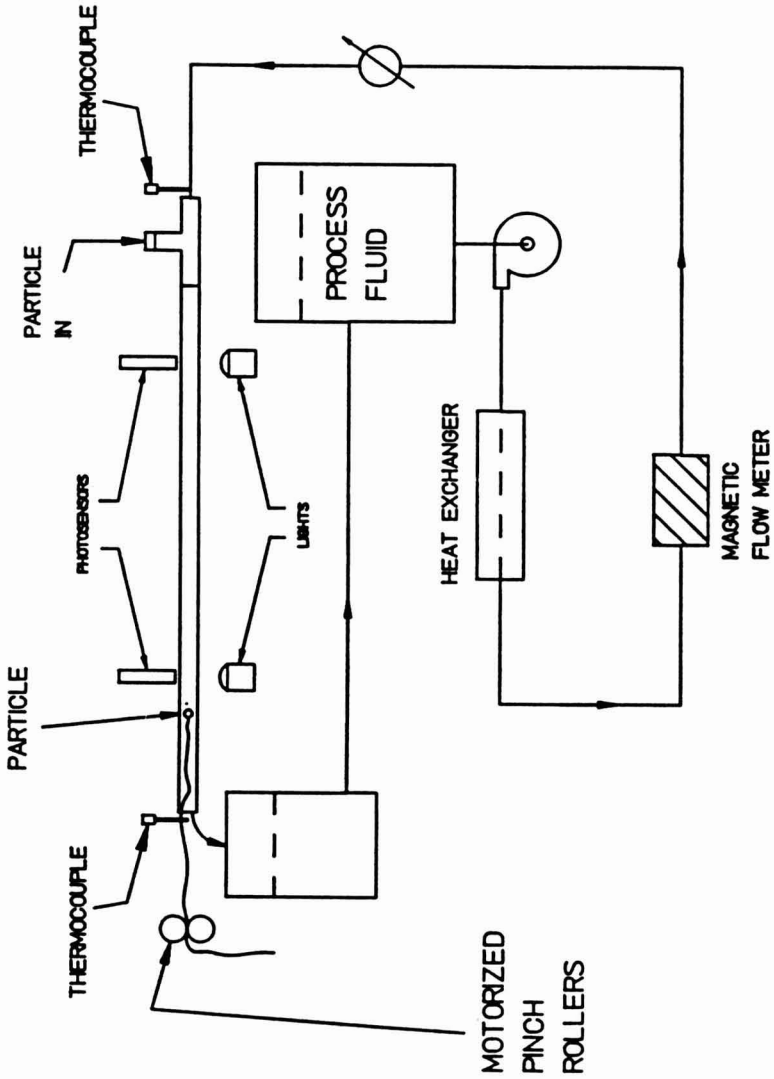


FIG. 1. SCHEMATIC DIAGRAM OF EXPERIMENTAL SETUP

TABLE I.  
DIMENSIONS AND PROPERTIES OF METAL TRANSDUCER PARTICLES

Particle Diameter (m)	Material	Specific Heat (kJ/kg°C)	Material Density (kg/m <sup>3</sup> )	Apparent Density of Hollow Particle (kg/m <sup>3</sup> )
0.0133	Brass	0.3540 <sup>b,c</sup>	8522 <sup>c</sup>	1060 <sup>a</sup>
0.0168	Brass	0.3540 <sup>b,c</sup>	8522 <sup>c</sup>	1030 <sup>a</sup>
0.0220	Aluminum	0.8996 <sup>d</sup>	2707 <sup>c</sup>	1012
0.0239	Aluminum	0.8996 <sup>d</sup>	2707 <sup>c</sup>	1006

<sup>a</sup>-Represents mean values from various experimental runs.

<sup>b</sup>-Value represents mass-average specific heat based on brass and an average of 12% solder.

<sup>c</sup>-Source, Holman (1981).

<sup>d</sup>-Source, CRC (1972).

always located on the inside wall of the particles, this necessitated dismantling of the particles and reattachment of thermocouple wires. With the aluminum particles, this was relatively easy because the spheres were made of precision-machined fitted hemispheres which could be dismantled. However, the brass hemispheres were stamped out of dies and had to be soldered together. Repair was difficult because the solder had to be melted down, thermocouples reattached, and the sphere refabricated with precise quantities of solder to ensure that apparent particle densities remained as close to constant as possible (some variation of about  $\pm 5 \text{ kg/m}^3$  was unavoidable). In all cases, the weight of solder used was determined and the effective specific heat of the particle was determined as a mass-average of the properties of brass and solder.

**Particle Damage.** During some of the tests, (0.0133 m particle, 0.0381 m tube) fluid leaked into the hollow particle through a pinhole, resulting in an unusually heavy sample. Data from these runs showed unusually slow thermal responses and erroneous values of  $h_{ip}$  were obtained which were not detected until the particle was disassembled. Consequently data for 70 experimental runs made in this study were discarded. After this experience, the particle mass was checked periodically to ensure that the density remained constant.

Finally, one of the aluminum spheres (0.0239 m diameter) was accidentally destroyed, and a new sphere was machined in its place, with a diameter of 0.022 m.

## Replications

A minimum of 8 and a maximum of 20 replications were performed at each set of experimental conditions. At the initial stages of the study, the number of replications was deliberately set at 20 to verify the reproducibility of the results. As the experimental techniques were mastered, the number of replications were reduced in number. In all, 251 useable experimental runs were conducted.

## Data Analysis

Data on mean values of  $h_{ip}$  as influenced by flow rate and particle to tube diameter ratio were analyzed using the Student's-t test (Steel and Torrie 1960). Dimensionless correlations were attempted, (using regression techniques) between the Nusselt number and various combinations of the following dimensionless parameters: fluid Reynolds number ( $Re_f$ ), particle Reynolds number ( $Re_p$ ), slip Reynolds number ( $Re_s$  based on slip velocity between fluid and particle), Froude number ( $Fr$ ), particle Froude number ( $Fr_p$ ) and particle to tube diameter ratio ( $d/D$ ). Definitions are as follows.

$$Re_f = V_r D \rho_f / \mu \quad (1)$$

$$Re_p = V_r d \rho_p / \mu \quad (2)$$

$$\text{Re}_s = (|V_p - V_f|d\rho_f)/\mu \quad (3)$$

$$\text{Fr} = V_f^2/gD \quad (4)$$

$$\text{Fr}_p = V_f^2/gd[(\rho_p/\rho_f) - 1] \quad (5)$$

Finally, values of Biot number ( $\text{Bi} = h_{fp}/k_p$ ) were checked after the experiment, to ensure that the basic premise of the analysis ( $\text{Bi} < 0.1$ ) was valid in all cases. The assumption was found to be valid in all cases, because of the small thickness (1) of the hollow metal spheres, and the high thermal conductivities of the metals used for construction.

## RESULTS AND DISCUSSION

Data on means and standard deviations of  $h_{fp}$  as influenced by flow rate and  $d/D$  ratio are presented in Table 2. Data show that in general, (with some individual exceptions) the value of  $h_{fp}$  increased with increasing fluid flow rate and  $d/D$  ratio. A plot of the data is presented in Fig. 2, showing the trends to be approximately linear in flow rate. The minimum and maximum values of  $h_{fp}$  measured in these studies were 688 and 3005  $\text{w/m}^2\text{C}$ , well above the values where the influence of  $h_{fp}$  on holding tube length would be significant (Lee and Singh 1988). These data encompass the range of values observed by Sastry *et al.* (1989), and fall partially in the range of values (1850 to 7300  $\text{w/m}^2\text{C}$ ) observed by Heppell (1985). The observations of Stoforos *et al.* (1989) also appear to be in the range of the present studies.

In all cases, the values of  $h_{fp}$  were considerably greater than would be expected from natural convection considerations alone. The dominance of forced convection was also borne out by comparing plots of log particle temperature ratio versus time to those of Alhamdan *et al.* (1990) for natural convection. Since natural convection driving forces change as equilibration occurs, a similar plot for natural convection shows a curved line, indicative of a time-variable heat transfer coefficient. In the present studies, consistently high regression coefficients ( $> 0.98$ ) were obtained, indicating a linear relationship, and thereby a constant value of  $h_{fp}$  over time. This observation supports the likelihood of a dominant, constant forced convection effect.

An interesting question is whether the results of these studies could be predicted by knowing the slip velocity ( $V_s$ ) and using the following well-known correlations of Kramers (1946), Ranz and Marshall (1952), and Whitaker (1972), represented by Eq. (6) through (8), respectively.

$$\text{Nu} = 2.0 + 1.3\text{Pr}^{0.15} + 0.66\text{Pr}^{0.31}\text{Re}_s^{0.5} \quad (6)$$

TABLE 2.  
MEANS, STANDARD DEVIATIONS ( $\sigma$ ) AND REPLICATIONS OF FLUID-TO-PARTICLE  
CONVECTIVE COEFFICIENT AT VARIOUS FLOW RATES AND PARTICLE TO TUBE  
DIAMETER (d/D) RATIOS

d/D ratio	Convective heat transfer coefficient, $h_p$ ( $W/m^2C$ )		
	0.000133	0.000266	Fluid flow rate ( $m^3/s$ ) 0.000465
0.2618	-	-	868.3 <sup>ap</sup> $\sigma = 124.7$ 8 reps
0.3307	-	939.5 <sup>ap</sup> $\sigma = 163.4$ 10 reps	1168.0 <sup>bp</sup> $\sigma = 340.2$ 10 reps
0.4331	-	1046.0 <sup>ap</sup> $\sigma = 118.8$ 10 reps	1571.8 <sup>ca</sup> $\sigma = 417.4$ 10 reps
0.4409	-	1516.6 <sup>ar</sup> $\sigma = 283.8$ 10 reps	2009.9 <sup>cr</sup> $\sigma = 156.8$ 10 reps
0.6273	1093.8 <sup>a</sup> $\sigma = 108.4$ 20 reps	1433.6 <sup>br</sup> $\sigma = 79.1$ 20 reps	1874.3 <sup>br</sup> $\sigma = 328.6$ 10 reps
		1886.7 <sup>ca</sup> $\sigma = 151.6$ 20 reps	2371.3 <sup>cn</sup> $\sigma = 402.4$ 10 reps
			2145.5 <sup>cr</sup> $\sigma = 201.2$ 10 reps
			2617.2 <sup>cs</sup> $\sigma = 179.8$ 20 reps

<sup>a,b,c,d,e</sup> - Mean values within the same row followed by the same letter were not significantly different ( $p < 0.05$ ).

<sup>p,q,r,s</sup> - Mean values within the same column followed by the same letter were not significantly different ( $p < 0.05$ ).

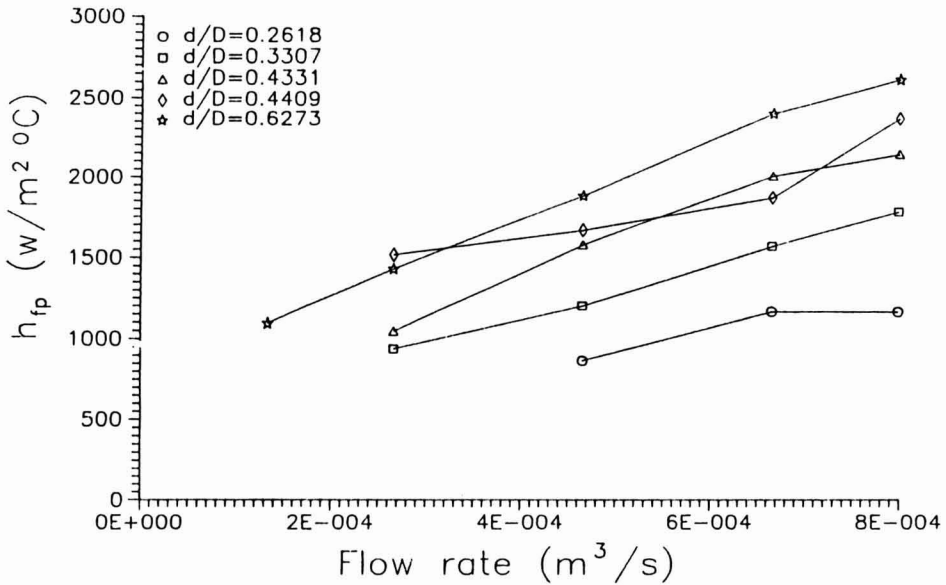


FIG. 2. PLOT OF HEAT TRANSFER COEFFICIENT ( $h_{fp}$ ) AS INFLUENCED BY FLUID FLOW RATE AND PARTICLE TO TUBE DIAMETER RATIO

$$\text{Nu} = 2.0 + 0.6\text{Re}_s^{0.5}\text{Pr}^{0.33} \quad (7)$$

$$\text{Nu} = 2.0 + (0.4\text{Re}_s^{0.5} + 0.06\text{Re}_s^{2/3})\text{Pr}^{0.4}(\mu/\mu_s)^{0.25} \quad (8)$$

It was possible to make such a comparison in the present studies, because particle velocities were directly measured in all cases, and fluid velocities were determinable from flow rates. Data on fluid, particle and slip velocities, and comparisons among  $h_{fp}$  values of these studies and those predicted by Eq. (6) through (8) are presented in Table 3. The results show moderate agreement under conditions of low  $d/D$  ratio and low flow rates, but significant underprediction at higher values of  $d/D$  ratio. This is to be expected, since the relations from the literature are for unbounded flow about a particle, while the present situation involves an enclosure at close proximity. As the  $d/D$  ratio increases, the presence of the wall assumes increasing importance. If the particle moves close to the wall, part of it is likely to be in contact with slow-moving fluid in the laminar sublayer, while the rest would likely be in contact with faster-moving bulk fluid, resulting in a complex distribution of relative velocity that is not easily predictable without simultaneous solution of the fluid/particle momentum relations.

An additional contributing factor is the occurrence of turbulence in the fluid. The flow rates in these studies were representative of those of commercial aseptic



TABLE 3.  
VALUES OF FLUID ( $V_f$ ), PARTICLE ( $V_p$ ) AND SLIP ( $V_s$ ) VELOCITIES, AND  
COMPARISONS OF CONVECTIVE COEFFICIENT ( $h_p$ ) EXPERIMENTAL VALUES, RANZ  
AND MARSHALL (1952) (R & M), KRAMERS (1946) AND WHITAKER (1972)  
RELATIONS, AS INFLUENCED BY FLOW RATE (Q) AND  $d/D$  RATIO

$d/D$	Q (m <sup>3</sup> /s)	Velocities (m/s)			Expt	$h_p$ (W/m <sup>2</sup> °C)		
		$V_f$	$V_p$	$V_s$		R & M	Kramers	Whitaker
0.2618	0.000462	0.2279	0.2080	- 0.0199	868.0	1024.3	1164.3	1045.9
	0.000661	0.3261	0.3080	- 0.0181	1168.5	980.9	1117.9	997.1
	0.000794	0.3917	0.3950	0.0033	1168.0	469.7	571.2	448.2
0.3307	0.000266	0.1312	0.1000	- 0.0312	939.5	1110.4	1242.2	1173.2
	0.000465	0.2294	0.2150	- 0.0144	1203.1	778.3	866.9	791.4
	0.000665	0.3281	0.3230	- 0.0051	1571.8	492.9	581.6	480.4
0.4331	0.000798	0.3937	0.3870	- 0.0067	1786.0	554.8	647.8	546.3
	0.000262	0.1293	0.1280	- 0.0013	1046.0	239.0	297.2	225.6
	0.000462	0.2279	0.2390	0.0111	1579.5	595.4	678.4	605.6
0.4409	0.000661	0.3261	0.3580	0.0319	2009.9	971.4	1080.5	1042.4
	0.000794	0.3917	0.4170	0.0253	2145.5	870.9	973.0	922.8
	0.000266	0.2333	0.2500	0.0167	1516.6	831.5	943.8	851.3
0.6273	0.000465	0.4079	0.4500	0.0421	1667.8	1277.7	1421.1	1371.9
	0.000665	0.5833	0.6290	0.0457	1874.3	1327.7	1474.6	1432.1
	0.000798	0.6999	0.7180	0.0181	2371.3	862.0	976.5	885.8
0.6273	0.000133	0.1167	0.1270	0.0103	1093.8	552.1	628.8	561.9
	0.000266	0.2333	0.2340	0.0007	1433.6	180.9	231.7	169.2
	0.000465	0.4079	0.4620	0.0541	1886.7	1195.8	1317.4	1329.6
0.6273	0.000665	0.5833	0.6170	0.0337	2403.8	954.7	1059.4	1032.5
	0.000798	0.6999	0.7420	0.0421	2617.2	1060.2	1172.3	1161.3

systems; however, the relatively inviscid carrier fluid (water) resulted in fluid Reynolds numbers ranging from 7300 to 43600. Thus, the significance of eddy velocities about particles cannot be discounted.

A further question concerns the spread in the data. The principal reason for variation between replications appears to be variations in the particle trajectory due to the interfering effects of the thermocouple wire. Although particle velocities were duplicated exactly, it was difficult to exactly replicate the same trajectory with a flexible, thin gauge thermocouple wire attached to the particle. It was noted that the thermocouple wire tended to curl over time. Although attempts were made to straighten it (this was done at the cost of increased risk of breakage), the physical characteristics would vary over the course of several replications. In addition, whenever thermocouple breakage occurred, a new wire would be installed, resulting in further unavoidable variations in installation. This is the principal limitation of the present experimental method. Other non-invasive techniques such as liquid crystals or thermal imaging may be useful not only in elimination of such variation, but also in accounting for particle rotation.

Regression between dimensionless groups resulted in a number of relations with varying quality of fit, depending on the complexity of the relation, and the number of combinations of dimensionless groups employed. The following relations were chosen based on goodness of fit, or on a combination of simplicity and satisfactory fit of data.

$$\text{Nu} = 26.81 + 0.00455\text{Re}_p(d/D) \quad (9)$$

$$(R^2 = 0.82)$$

$$\text{Nu} = 6.023 \times 10^{-6}\text{Re}_p^{1.79}(d/D)^{1.71}\text{Fr}_p^{-0.64} \quad (10)$$

$$(R^2 = 0.86)$$

$$\text{Nu} = 0.0046\text{Re}_p + 41.54(d/D) - 35.65\text{Fr}_p - 5.24 \quad (11)$$

$$(R^2 = 0.89)$$

$$\text{Nu} = 0.0125\text{Re}_p + 85.67(d/D) - 342.5\text{Fr}_p - 0.0144\text{Re}_p(d/D) \quad (12)$$

$$+ 0.0113\text{Re}_p\text{Fr}_p + 500.3\text{Fr}_p(d/D) - 0.0173\text{Re}_p\text{Fr}_p(d/D) - 26.56$$

$$(R^2 = 0.92)$$

Equations (9) through (12) have the following ranges of applicability:

$$3600 < \text{Re}_p < 27300; 0.2618 < d/D < 0.6273; 0.39 < \text{Fr}_p < 14.83.$$

It is recognized that the above results do not include the  $d/D = 0$  and  $\text{Re}_p = 0$  asymptotes, but the major purpose of the present study was to obtain

typical representative data for a holding tube type situation, rather than develop a general relationship.

A plot of Nusselt number versus  $Re_p(d/D)$  presented in Fig. 3, shows the fit of the simple correlation (8). It is worth noting that both the fluid and particle Reynolds numbers yielded considerably better correlations than the slip Reynolds number. The reason may well be the presence of the wall boundary, which restricts fluid velocities at the wall, and causes a sharp fluid velocity profile in its vicinity. The true relative velocity between the particle and fluid would then be expected to be greater than the slip velocity as calculated in this work.

It would not be truly valid to compare these results to those of Chau and Snyder (1988); Chandarana *et al.* (1988, 1989); Chang and Toledo (1989), because of the widely different conditions of experiment; however, it may be noted that the studies of Chandarana *et al.* and Chang and Toledo have been conducted under low relative velocities (typically less than 0.01 m/s), while the slip velocities of these studies have been considerably greater than their values. In addition, the other studies have involved stationary particles that appear to have been further away from system boundaries than in these studies.

A final point worth considering is the influence of increased carrier viscosity, which would be expected to move the flow regime into the laminar zone, and reduce heat transfer coefficients. In addition, effects such as dilatancy (Dail

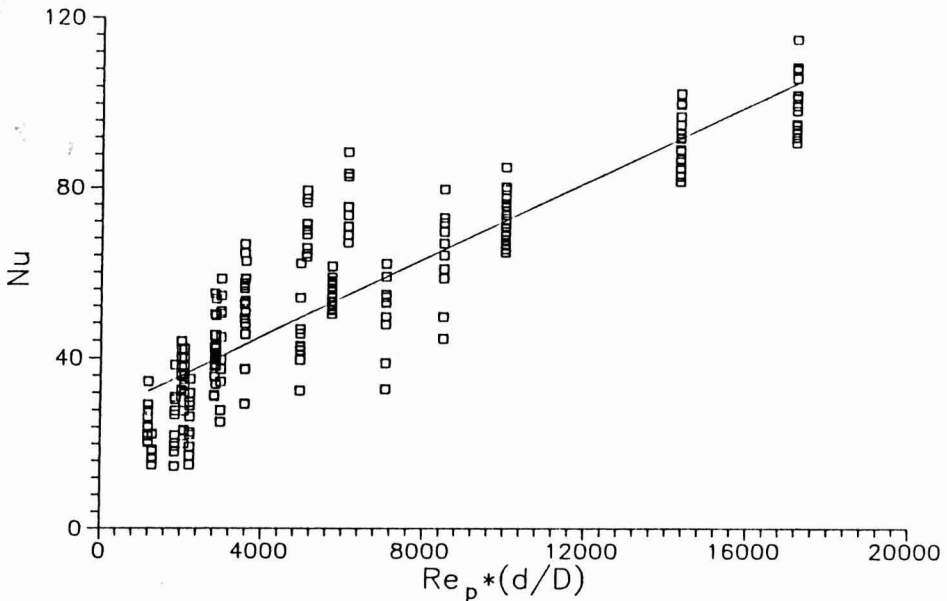


FIG. 3. PLOT OF NUSSULT NUMBER VERSUS PRODUCT OF PARTICLE REYNOLDS NUMBER AND PARTICLE TO TUBE DIAMETER RATIO

1989) may complicate matters under UHT conditions. These points merit further investigation. Studies with viscous fluids are in progress and will be reported at a later stage.

## CONCLUSIONS

Fluid-to-particle convective heat transfer coefficients were found to increase significantly with increasing fluid flow rate and particle to tube diameter ratio. Heat transfer coefficients were found to range from 688 to 3005  $\text{W/m}^2\text{°C}$  over the range of conditions studied. These data suggest that the effective relative velocity between fluid and particle is significantly influenced by the presence of the wall, and that wall effects increase in importance as the particle to tube diameter ratio increases. Various regression equations relating the Nusselt number with the particle Reynolds and Froude numbers, and the particle to tube diameter ratio, had  $R^2$  values from 0.82 to 0.92 depending on the complexity of the relation.

## LIST OF SYMBOLS

Bi	Biot number = $h_{fp}l/k_p$
$C_{pf}$	Specific heat of fluid ( $\text{J/kg}^\circ\text{C}$ )
d	Particle diameter (m)
D	Tube diameter (m)
Fr	Froude number (defined in eq. 4)
$Fr_p$	Particle Froude number (defined in eq. 5)
g	Gravitational acceleration ( $\text{m/s}^2$ )
$h_{fp}$	Fluid-to-particle convective heat transfer coefficient ( $\text{W/m}^2\text{°C}$ )
$k_f$	Thermal conductivity of fluid ( $\text{W/m}^\circ\text{C}$ )
$k_p$	Thermal conductivity of particle ( $\text{W/m}^\circ\text{C}$ )
l	Wall thickness of metal particle (m)
Nu	Nusselt number = $h_{fp}d/k_f$
$Re_f$	Fluid Reynolds number (defined in eq. 1)
$Re_p$	Particle Reynolds number (defined in eq. 2)
$Re_s$	Slip Reynolds number (defined in eq. 3)
$V_f$	Mean fluid velocity (m/s) = flow rate/cross sectional area
$V_p$	Particle velocity (m/s)
$\mu$	Viscosity of bulk fluid (Pa.s)
$\mu_s$	Viscosity of fluid at particle surface (Pa.s)
$\rho_f$	Density of fluid ( $\text{kg/m}^3$ )
$\rho_p$	Density of particle ( $\text{kg/m}^3$ )

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