

MODELLING OF HEAT TRANSFERS AND PREDICTION OF CRYSTALLIZATION DURING COOLING OF CHICKEN FAT

E. Arnaud*, G. Trystram^o, P. Relkin^o, A. Collignan*

* CIRAD, BP 20, 97408 Saint Denis Messag. Cedex 9, France
elodie.arnaud@cirad.fr, antoine.collignan@cirad.fr

(phone: 262 (0) 262 92 24 48 / 262 (0) 262 92 24 47, fax: 262 (0) 262 92 24 31)

^o ENSIA, 1 avenue des Olympiades, 91744 Massy Cedex, France
trystram@ensia.fr, relkin@ensia.fr

(phone: 33 (0) 1 69 93 50 65 / 33 (0) 1 69 93 50 29, fax: 33(0)1 69 93 51 85 / 33 (0)1 69 93 50 05)

ABSTRACT

Heat transfers that occurred during chicken fat dry fractionation process were characterized. The heat flux model developed led to follow the heat flux associated with crystallization (ϕ_r) during the cooling step. A crystallization kinetics was performed by measuring the solid content of the suspension of crystals at regular intervals by low-resolution pulsed nuclear magnetic resonance. The variation of the total heat of crystallization calculated from the thermal model developed in this study was in good agreement with the crystallization kinetics. The results reported suggested that monitoring ϕ_r during cooling could be useful for the prediction and control of crystallization kinetics and therefore the yield of fat dry fractionation process.

INTRODUCTION

Fat consists of a mixture of triglycerides with different melting points. The fat dry fractionation process involves selective crystallization of the highest melting point triglycerides followed by filtration. This leads to separation of a solid fraction (stearin) with a higher saturated fatty acid content and a liquid fraction (olein) with a higher unsaturated fatty acid content. Dry fractionation is currently used for processing a broad range of fats (palm oil, palm kernel oil, milk fat, fish oil, lard, etc.) with the aim of eliminating the most saturated compounds in order to enhance the winterisation potential of oils, boosting the unsaturated fatty acid content, or even obtaining fractions with special rheological properties. Dry fractionation of chicken fat, a semi solid fat in its natural state with good nutritional properties compared with other animal fats, leads to a solid fat fraction whose physical characteristics resembles that of lard and tallow [1].

Cooling is a key factor in triggering crystallization and controlling subsequent crystal development. The cooling conditions have an effect on crystal number and size, and therefore on the quality of the separated fractions [2-4].

During cooling, heat is released from the fat through an exothermic process which will be partially offset by the cooling system of the reactor. Factors such as fat viscosity (which increases during crystallization), the heat exchange surface between the fat and the reactor walls, and the agitation conditions have a marked impact on heat transfers [2, 5].

Numerous studies have been done on crystallization, in particular in chemistry, sugar-producing or lipid processing. But no studies to date have characterized heat exchanges that occur during fat dry fractionation.

The aim of the present study was thus to model heat transfers during chicken fat dry fractionation process, and assess the performance of the model for simulating the crystallization kinetics during this process.

MATERIAL & METHODS

Experimental design

Fat dry fractionation was performed in a 2 L jacketed glass reactor, agitated and connected to a circulating water bath (Fig. 1). Heating and cooling were controlled by monitoring the temperature of the water circulating within the reactor double walls. Two Pt 100 temperature probes were used to measure the temperature of the fat (T_f) in the reactor and that of the circulating water bath (T_{cw}). The temperature of external environment (T_{ext}) was measured with a NiCrNi type K thermocouple. Temperatures were recorded every minute through an ALMEMO 2290-8 data logger. A slow agitation rate (0.078 m/sec) was used in order to have a homogenous temperature in the reactor without breaking crystals being formed.

Raw material

Chicken fat was obtained after melting abdominal fat at 90-100°C, eliminating the collagenic by-products by filtration and the liquid fraction by decantation. Abdominal fat came from a local slaughter house. Then 2 kg fat samples were poured into glass bottles and stored at -20°C.

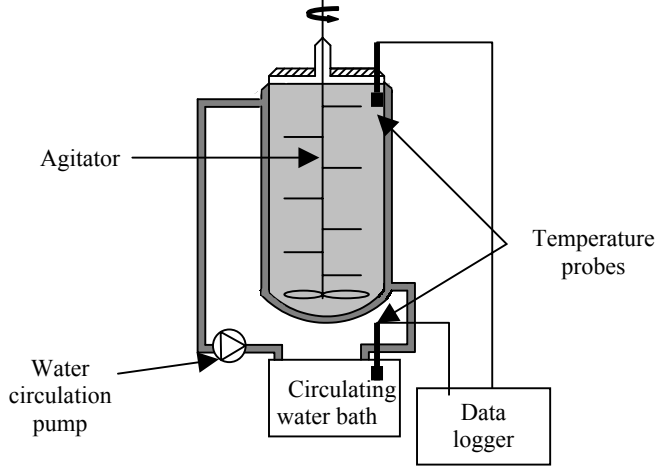


Fig. 1: Diagram of the experimental fractionation apparatus.

Theoretical framework of the thermal model

Taking into account heat transfers and fat crystallization under the cooling treatment (Fig. 2), the energy balance can be expressed as follows:

$$\phi_r = \phi_{accu} + \phi_{flow} + \phi_{loss} \quad (1)$$

Heat induced by the stirrer was considered negligible due to the slow agitation rate used.

Considering a time interval dt , the different heat flux can be expressed as (Fig. 2):

$$\phi_r = \frac{dm_c}{dt} \Delta h_c \quad (2)$$

Δh_c is considered to be constant during the time interval dt .

$$\phi_{accu} = m_f C_{p_f} \frac{dT_f}{dt} \quad (3)$$

Fat temperature (T_f) measured at different points in the reactor varied by less than 0.3°C. Specific heat of fat (C_{p_f}) value (2000 J.kg⁻¹.K⁻¹) is mean of previously published data for other fats [6] and was considered to be constant throughout the treatment.

$$\phi_{flux} = \int_{A_1} (T_f - T_{cw}) U_f dA_1 \quad (4)$$

Cooling water temperature (T_{cw}) was considered constant as temperature differences between the reactor double walls inlet and outlet were of the order of experimental probes error.

$$\phi_{loss} = \int_{A_2} (T_f - T_{ext}) K dA_2 \quad (5)$$

The heat exchange surface A_1 (0.082 m²) between water and fat was assumed to be flat and the heat flux through the glass were considered to be unidirectional due to the thinness of the glass over the radius of the reactor.

Similarly, fat was separated from the external environment by an air layer and a glass wall of area A_2 (0.0078 m²) and constant thickness.

The general heat balance equation after integration of the heat exchange surfaces is:

$$\frac{dm_c}{dt} \Delta h_c = m_f C_{p_f} \frac{dT_f}{dt} + (T_f - T_{cw}) U_f A_1 + (T_f - T_{ext}) K A_2 \quad (6)$$

When considering a time interval Δt , Eq.(6) becomes:

$$\frac{m_{c_{t+\Delta t}} - m_{c_t}}{\Delta t} \Delta h_c = m_f C_{p_f} \frac{T_{f_{t+\Delta t}} - T_{f_t}}{\Delta t} + \left(\frac{T_{f_{t+\Delta t}} + T_{f_t}}{2} - \frac{T_{cw_{t+\Delta t}} + T_{cw_t}}{2} \right) U_f A_1 + \left(\frac{T_{f_{t+\Delta t}} + T_{f_t}}{2} - T_{ext} \right) K A_2 \quad (7)$$

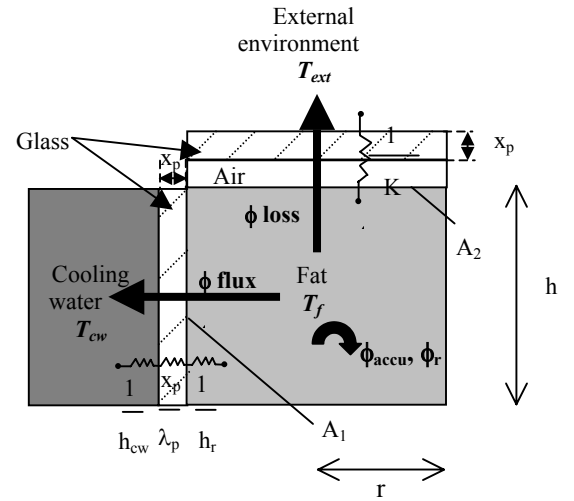


Fig. 2: Schematic diagram of heat flux.

Experimental strategy used to follow heat flux associated with crystallization

Quantification of U and K in the temperature range of fat crystallization was based on a first experiment performed with water in the reactor.

$$\text{Then, } \frac{m_{c_{t+\Delta t}} - m_{c_t}}{\Delta t} \Delta H_c = 0.$$

Thus, Eq.(7) becomes:

$$- m_w C_{p_w} \frac{T_{w_{t+\Delta t}} - T_{w_t}}{\Delta t} = \left(\frac{T_{w_{t+\Delta t}} + T_{w_t}}{2} - \frac{T_{cw_{t+\Delta t}} + T_{cw_t}}{2} \right) U_{exp} A_1 + \left(\frac{T_{w_{t+\Delta t}} + T_{w_t}}{2} - T_{ext} \right) K A_2 \quad (8)$$

When $T_{ext} = \frac{T_{w_{t+\Delta t}} + T_{w_t}}{2}$, U_{exp} can be deduced experimentally from the following relation:

$$-m_w C_{p_w} \frac{T_{w_{t+\Delta t}} + T_{w_t}}{\Delta t} = \left(\frac{T_{w_{t+\Delta t}} + T_{w_t}}{2} - \frac{T_{c_{w_{t+\Delta t}}} + T_{c_{w_t}}}{2} \right) U_{exp} A_1 \quad (9)$$

Knowing U_{exp} , K could be calculated for each time interval Δt from the kinetics data (Eq.(8)).

$\frac{1}{U}$ can be defined in terms of resistances (Fig. 2):

$$\frac{1}{U} = \frac{1}{h_{cw}} + \frac{x_p}{\lambda_p} + \frac{1}{h_r} \quad (10)$$

$\frac{1}{h_{cw}}$, $\frac{x_p}{\lambda_p}$ and K are not affected by the nature of the fluid

in the reactor. However, the $\frac{1}{h_r}$ value identified with water

in the reactor was no longer valid for the fat. The rheological characteristics of the fat differed substantially, which modified the flux regime and thus the thermal resistance at the fat/pyrex interface.

Using Reynolds and Prandtl numbers (Tab. 1), calculation of $\frac{1}{h_{cw}}$, $\frac{x_p}{\lambda_p}$ and $\frac{1}{h_r}$ allowed us to calculate the

contribution of $\left(\frac{1}{h_{cw}} + \frac{x_p}{\lambda_p} \right)_{cal}$ to $\left(\frac{1}{U} \right)_{cal}$.

In the same time, $\frac{1}{h_r}$ value for fat was calculated on the basis of the experimental fat viscosity measurements (Tab. 1).

Knowing U_f and K , it was possible to calculate the heat flux associated with crystallization ϕ_r (Eq.(7)).

Experimental procedure

1.76 kg of fat (or water) was placed in the reactor. Fat was first melted at 70°C. The cooling water circulating within the reactor double walls was cooled at a rate of 1°C/min until it reached 11°C, where it was maintained until the end of the treatment for.

The crystallization kinetics was performed by measuring the solid fat content of the suspension of crystals during cooling at regular intervals by low-resolution pulsed nuclear magnetic resonance using an RMN Minispec PC/120 spectrometer (Bruker Spectrospin, France). The spectrometer was calibrated against three reference samples.

Fat viscosity was determined over a time course by placing 400 ml of fat in a beaker immersed in a water bath and cooled under the same conditions as described for the crystallization step. The fat viscosity was measured during the experiment using a Brookfield Model DV II viscometer.

RESULTS & DISCUSSION

Identification of thermal exchange coefficients

Fig. 3 shows variations of temperature of the water in the reactor and the cooling water during the process. On the basis of these experimental data, it was possible to calculate U_{exp} for water in reactor when the temperature of the water in the reactor was the same as the external temperature, i.e. 27.9°C, which gives:

$$U_{exp} = 106 \text{ W/K m}^2 \quad (11)$$

Tab. 1: Values for the parameters used and

calculations for $\frac{1}{h_{cw}}$, $\frac{x_p}{\lambda_p}$ and $\frac{1}{h_r}$.

ρ_{cw}	1 045
ρ_w	1 000
ρ_f	900
V_{cw}	0.01
V_w, V_f	0.078
h	0.21
r	0.05
μ_{cw}	0.0019
μ_w	0.001008
μ_f at 25°C	0.068
$C_{p_{cw}}, C_{p_w}$	4 177
C_{p_f}	2 000
λ_{cw}	0.42
λ_w	0.6
λ_f	0.145
λ_p	1.5
x_p	0.0035
Calculation of $1/h_{cw}$	
$Re = \rho_{cw} \cdot V_{cw} \cdot h / \mu_{cw}$	1 155 laminar regime
$Pr = C_{p_{cw}} \cdot \mu_{cw} / \lambda_{cw}$	19
$h_{cw} = 0.664 \cdot Re^{1/2} \cdot Pr^{1/3} \cdot \lambda_{cw} / h$	119
$1/h_{cw}$	$(8.4 \pm 0.8) 10^{-3}$
Calculation of x_p / λ_p	
x_p / λ_p	$(2.3 \pm 0.6) 10^{-3}$
Calculation of $1/h_r$ (water experiment)	
$Re = \rho_w \cdot V_w \cdot 2\pi r / \mu_w$	24 310 turbulent regime
$Pr = C_{p_w} \cdot \mu_w / \lambda_w$	7
$h_r (\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}) = 0.036 \cdot Re^{0.8} \cdot Pr^{1/3} \cdot \lambda_w / 2\pi r$	422
$1/h_r$	$(2.4 \pm 0.001) 10^{-3}$
Calculation of $1/h_r$ (fat experiment at 25°C)	
$Re = \rho_f \cdot V_f \cdot 2\pi r / \mu_f$	324 laminar regime
$Pr = C_{p_f} \cdot \mu_f / \lambda_f$	938
$h_r = 0.664 \cdot Re^{1/2} \cdot Pr^{1/3} \cdot \lambda_f / 2\pi r$	53
$1/h_r$	$18.9 10^{-3}$

The calculation of $\frac{1}{h_{cw}}, \frac{x_p}{\lambda_p}$ and $\frac{1}{h_r}$ on the basis of the numbers of Reynolds and Prandlt (Tab. 1) shows that:

$$\left(\frac{1}{h_{cw}} + \frac{x_p}{\lambda_p}\right)_{cal} = 0.82 \left(\frac{1}{U}\right)_{cal} \quad (12)$$

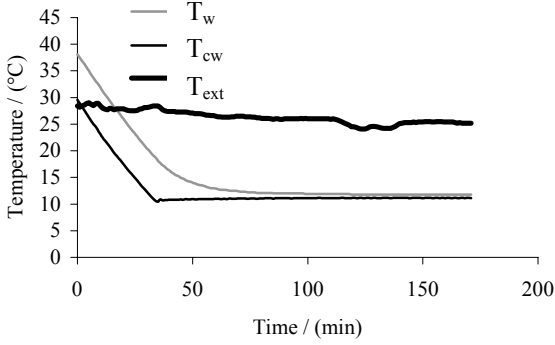


Fig. 3: Variations of the temperature of water in the reactor, cooling water and external temperature during cooling.

When considering Eq.(11) and Eq.(12), it can be concluded that:

$$\frac{1}{h_{cw}} + \frac{x_p}{\lambda_p} = 0.82 \frac{1}{U_{exp}} = 7.7 \cdot 10^{-3} \text{ K m}^2/\text{W} \quad (13)$$

We can note that $\left(\frac{1}{U}\right)_{cal} = (13.1 \pm 1) \cdot 10^{-3} \text{ K m}^2/\text{W}$ which is the same order of magnitude as $\frac{1}{U_{exp}}$.

For each time interval Δt , K is calculated by the following equation:

$$K = \frac{-\phi_{accu} - \phi_{flow}}{\frac{T_{w_t + \Delta t} + T_{w_t}}{2} - T_{ext}} \frac{1}{A_2} \quad (14)$$

Variation of K according to the water temperature in the reactor is shown in Fig. 4. The K values obtained for each time interval Δt were smoothed by polynomial functions that differed according to the temperature ranges. K depended on the temperature of the water in the reactor, the external temperature and natural convective movements associated with the difference in water and air temperatures. The pattern was therefore not linear.

Fig. 5 shows the variation of chicken fat viscosity during cooling.

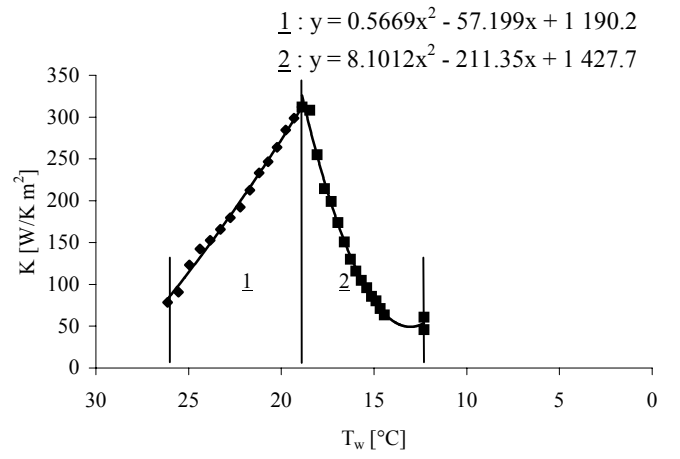


Fig. 4: Variation of K according to the water temperature in the reactor with polynomial smoothing of this variation.

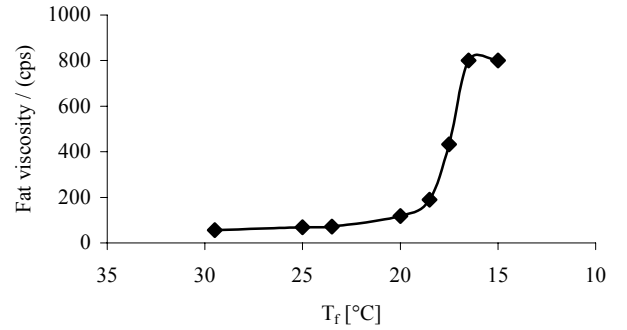


Fig. 5: Variation of chicken fat viscosity during cooling.

From fat viscosity values, $\frac{1}{h_r}$ was calculated (Tab. 1).

$\frac{1}{h_r}$ variation versus fat temperature was smoothed by polynomial functions that differed according to the temperature ranges (Fig. 6).

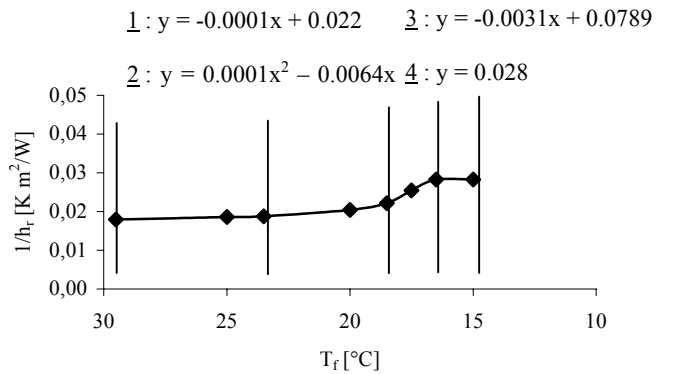


Fig. 6: Variations of $\frac{1}{h_r}$ according to fat temperature and polynomial smoothing of this variation.

$$\text{Thus, for the fat: } \frac{1}{U_f} = 7.7 \cdot 10^{-3} + \frac{1}{h_r} (T_f) \quad (15)$$

Thermal model heat flux associated with crystallization and experimental crystal mass kinetics

Variation of fat and cooling water temperatures during the process are shown in Fig. 7. We found that, as compared to water (Fig. 3), the fat cooled more slowly and levelled off at 1.85°C above the cooling water temperature. The fat cooling rate was lower than that of the water due to crystallization and also to the increase in $\frac{1}{h_r}$ values.

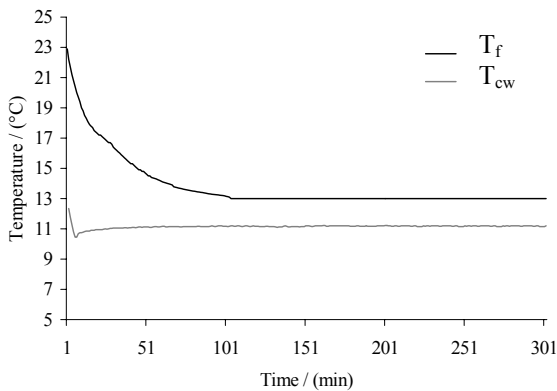


Fig. 7: Variations of fat and cooling water temperatures during cooling.

Variation of total heat of crystallization (total ϕ_r) and the experimental crystallization kinetics are shown Fig. 8.

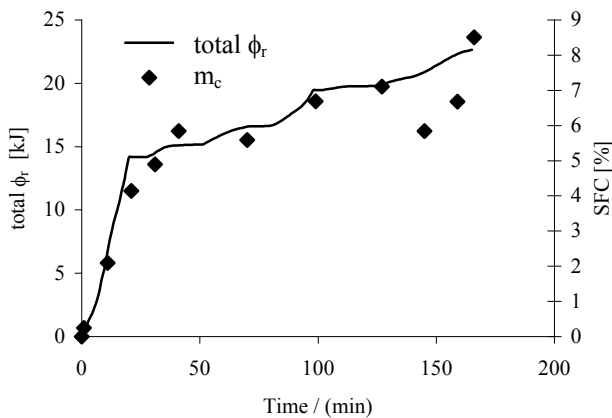


Fig. 8: Variations of total heat of crystallization and solid fat content of the suspension of crystals

Variation of total heat of crystallization calculated with the thermal model is in good agreement with the experimental crystallization kinetics.

Stearin mass obtained after filtration depends on the crystal mass formed during crystallization and the proportion of liquid phase occluded during the filtration step.

For a temperature T :

$$C_p(T) = C_{p \text{ solid state}} \times SFC + C_{p \text{ liquid state}} \times (100 - SFC)$$

The solid fat content of the suspension is less than 10% (Fig. 8). For example, $C_{p \text{ liquid state}} = 1295 \text{ J/kg K}$ et $C_{p \text{ solid state}} = 2006 \text{ J/kg K}$ for lard [6]. At the end of the cooling, the C_p value is 1935 J/kg K . So, the assumption that C_p is constant throughout the treatment can be done as the solid content of the suspension is not high.

CONCLUSION

The thermal analysis of chicken fat dry fractionation process shed fresh light on the nature and extent of the heat transfers involved.

The proposed model—based on a progressive experimental approach—allowed us to follow the heat flux associated with crystallization (ϕ_r) during cooling.

The comparison of the variation of the total heat of crystallization and the crystallization kinetics suggested that monitoring ϕ_r during cooling could be useful for the prediction and control of crystallization kinetics and therefore the process yield.

NOMENCLATURE

Symbol	Quantity	SI Unit
A_1	exchange area between fat and cooling water	m^2
A_2	exchange area between fat and external environment	m^2
$C_{p_{cw}}$	specific heat of cooling water	J/kg K
C_{p_f}	specific heat of fat	J/kg K
C_{p_w}	specific heat of water	J/kg K
dA	heat exchange element	m^2
h	level of cooling water in the reactor double walls	m
h_{cw}	convective heat transfer coefficient of cooling water	W/K m^2
h_r	convective heat transfer coefficient of reactor content	W/K m^2
K	thermal exchange coefficient between fat and external environment	W/K m^2
m_c	crystals mass	kg
m_f	fat mass	kg
m_w	water mass	kg
r	reactor radius	m
SFC	solid fat content	g/100g
T_{cw}	temperature of cooling water	K
T_{ext}	temperature of external environment	K
T_f	temperature of fat	K
T_w	temperature of water	K
U_{exp}	thermal exchange coefficient between water and cooling water	W/K m^2
U_f	thermal exchange coefficient between fat and cooling water	W/K m^2
$(\frac{1}{U})_{cal}$	resistance between water and cooling water calculated using Reynolds and Prandtl numbers	$\text{K m}^2/\text{W}$
V_{cw}	velocity of cooling water	m/sec

V_f	velocity of fat	m/sec
V_w	velocity of water	m/sec
x_p	pyrex thickness	m
λ_{cw}	conductivity of cooling water	W/K m
λ_f	Conductivity of fat	W/K m
λ_w	conductivity of water	W/K m
λ_p	conductivity of pyrex	W/K m
Δh_c	heat of crystallization	J/kg
ϕ_{accu}	accumulated heat in the reactor	W
ϕ_{flux}	heat flux between fat and cooling water circulating within the reactor double walls	W
ϕ_{loss}	heat loss through reactor lid	W
ϕ_r	heat flux associated with crystallization reaction	W
μ_f	viscosity of fat	kg/m sec
μ_{cw}	viscosity of cooling water	kg/m sec
μ_w	viscosity of water	kg/m sec
ρ_f	density of fat	kg/m ³
ρ_{cw}	density of cooling water	kg/m ³
ρ_w	density of water	kg/m ³

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