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‘Evaluation of circulation and heat transfer in calandria tubes of crystallisation vacuum pans’

Thesis submitted by

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for the degree of Masters of Engineering Science
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ABSTRACT

This thesis investigates the importance of circulation and heat transfer in crystallisation vacuum pans that produce raw sugar in the sugar mill. The driving force for circulation and heat transfer occurs in the calandria tubes within vacuum pans.

Numerical and CFD modelling is becoming a cost-effective and reliable way of developing vessel designs especially when there are complex physics and geometries involved, as is the case with vacuum pans. Currently, however, there are no working numerical models of vacuum pans that can be confidently used to design pans with improved circulation and boiling. If the operation of vacuum pans and specifically calandria tubes can be adequately modelled, the design of industrial vacuum pans can be improved to realise the benefits of obtaining more efficient circulation and heat transfer within the pan.

The research aims to provide data on heat transfer and circulation in factory crystallisation vacuum pans and provide data on an experimental rig simulating a single calandria tube for validation of numerical models. Factory trials were conducted to obtain data on heat transfer and circulation in factory pans. A method for measuring circulation speeds in massecuite solutions and vacuum pans was refined as part of this research. The data collected from the factory trials enabled the operating conditions for the single calandria tube boiling rig experimental trials to be determined.

The intention of the experimental rig was to simulate factory conditions to allow detailed examinations of the heat transfer process and vapour volume fraction profiles to be obtained. Natural and forced circulation conditions were investigated as both types of circulation are present in factory vacuum pans. The data gathered from these experiments were preliminary in nature as the rig did not adequately represent factory equipment.

The research highlights problems associated with the boiling of viscous fluids, such as molasses on a laboratory scale. Strategies and recommendations are provided to enable a more adequate representation of factory conditions in the experimental rig. These improvements will allow more accurate data to be obtained that can be used to develop improved models of calandria tubes and vacuum pans.

The experiments conducted on the single calandria tube detailed the physical changes and heat transfer characteristics for boiling in calandria tubes with changing material properties and heat input conditions. The experiments allowed fluid specific correlations to be obtained for heat transfer coefficients and vapour distribution during boiling in the calandria tubes. These correlations were used to develop numerical models of the boiling that occurs in calandria tubes. The numerical models provided a better understanding of the flow characteristics in the vessel and can facilitate the development of improved engineering designs.

The project shows the applicability of a pilot scale rig to provide data that can be used to improve the understanding and modelling of flow and heat transfer in the calandria tubes of crystallisation vacuum pans.

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DECLARATION

I declare that this thesis is my own work and has not been submitted in any form for another degree or diploma at any university or other institution of tertiary education. Information derived from the published or unpublished work of others has been acknowledged in the text and a list of references is given.

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LIST OF SYMBOLS

A_{film}	Heat transfer area of metal film	m^2
A_{HT}	Heat transfer area	m^2
A_{tube}	Surface area of the calandria tube	m^2
A_R	Entrained air constant for viscosity calculations	-
Bo	Non-dimensional Bond number	-
BPE	Boiling point elevation of the massecuite	ºC
BPE_S	Boiling point elevation of the sugar solution	ºC
Bx_{liq}	Brix of the sugar solution	%
Bx_{mass}	Brix of the massecuite	%
Bx_{mol}	Brix of the molasses	%
$\mathrm{C_Y}, \mathrm{C_X}, \mathrm{n_K}$	King's law constants	-
C_0	Flow distribution parameter	-
CC_{mass}	Crystal content by weight of massecuite	%
CC_{vol}	Volume ratio of crystal to molasses in the solution	%
$C_{p,liq}$	Specific heat of the sugar solution	$J.kg^{-1}.K^{-1}$
$C_{p,mass}$	Specific heat of the liquid	$J.kg^{-1}.K^{-1}$
$C_{p,sug}$	Specific heat of the sugar	$J.kg^{-1}.K^{-1}$
C_N	Count rate for the process fluid in the heated tube	$counts.s^{-1}$
CV	Coefficient of variation in the crystal size distribution	%
C_W	Count rate for a fluid with specific gravity of unity	$counts.s^{-1}$
d_{bub}	Diameter of the bubble	m
dP_{grav}	Pressure loss due to elevation	$N.m^{-2}$
dP_{acc}	Pressure loss due to acceleration	$N.m^{-2}$
dP_{frict}	Pressure loss due to friction	$N.m^{-2}$
D	Internal diameter of the heated tube	m
DS_{liq}	Dry substance of the solution	%
DS_{mass}	Dry substance of the massecuite	%
DS_{mol}	Dry substance of the mother molasses	%
E	Voltage output of the anemometer	Volt
F_R	Crystal property constant for viscosity calculations	-
f_f	Fanning friction factor	-
f_{liq}	Fanning friction factor evaluated for the liquid velocity	-
f_{vap}	Fanning friction factor evaluated for the vapour velocity	-
g	Gravitational acceleration constant	$m.s^{-2}$

G	Mass flow rate in the tube	$kg.s^{-1}$
h_{boil}	Boiling heat transfer coefficient	$W.m^{-2}.K^{-1}$
h_{cond}	Condensation heat transfer coefficient	$W.m^{-2}.K^{-1}$
h_{conv}	Convection heat transfer coefficient	$W.m^{-2}.K^{-1}$
h_{FC}	Forced convection heat transfer coefficient	$W.m^{-2}.K^{-1}$
h_{NB}	Nucleate boiling heat transfer coefficient	$W.m^{-2}.K^{-1}$
h_{SP}	Single phase transfer coefficient	$W.m^{-2}.K^{-1}$
h_{TP}	Boiling or two-phase heat transfer coefficient	$W.m^{-2}.K^{-1}$
I	Current in the heating element	A
Ja	Non-dimensional Jacob number	-
k_{liq}	Thermal conductivity of the sugar solution	$W.m^{-1}.K^{-1}$
k_{mass}	Thermal conductivity of massecuite	$W.m^{-1}.K^{-1}$
K_{liq}	Consistency of the liquid	$N.m^{-2}.s^{n}$
L_{xal}	Mean crystal size	mm
L_{D}	Path length of the process fluid	m
L	Length scale for heat transfer	m
L_{T}	Length of the heated tube	m
M_{AC}	Mass absorption coefficient	$m^{2}.kg^{-1}$
M_{CW}	Mass flow rate of the cooling water stream	$kg.s^{-1}$
M_{leak}	Leakage mass flow rate of air	$kg.h^{-1}$
M_{steam}	Mass flow rate of the steam	$kg.s^{-1}$
MW	Molecular weight	$kg.kmol^{-1}$
n_{flow}	Viscosity flow behaviour index	-
N_{bub}	Experimentally determined constant (Equation 4.22)	-
Nu_{L}	Non-dimensional Nusselt number	-
Nu_{TP}	Non-dimensional two-phase Nusselt number	-
p	Static pressure in the heated tube	kPa
P_{liq}	True purity of the solution	%
P_{mass}	True purity of the massecuite	%
P_{mol}	True purity of the mother molasses	%
Pr	Non-dimensional Prandtl number	-
Q	Heat flux	W
Q_{cond}	Heat flux in the heat exchanger	W
Q_{leak}	Air leakage rate in the rig	$m^{3}.Pa.s^{-1}$
Q_{liq}	Volumetric flow rate of liquid in the tube	$m^{3}.s^{-1}$
Q_{tube}	Heat flow rate to the calandria tube	W
Q_{vap}	Volumetric flow rate of vapour in the tube	$m^{3}.s^{-1}$

r	Internal radius of the heated tube	m
R	Gas constant	8.314 $m^3.Pa.mol^{-1}.K^{-1}$
Re_{TP}	Non-dimensional two-phase Reynolds number	-
R_m	Metal heating element resistance	Ω
R_{SW}	Heating resistance from the condensing steam to the tube	$W^{-1}.^{o}C$
R_{WM}	Heating resistance from the tube wall to the massecuite	$W^{-1}.^{o}C$
S	Liquid – vapour slip ratio	-
$\mathrm{suc}_{\mathrm{liq}}$	Sucrose content of the solution	%
T_a	Ambient fluid temperature	ºC
T_{air}	Temperature of the air leaking into the system	ºC
T_{CWin}	Inlet cooling water temperature	ºC
T_{CWout}	Outlet cooling water temperature	ºC
T_f	Film temperature	ºC
T_{liq}	Temperature of the liquid	ºC
T_{mass}	Temperature of the massecuite	ºC
T_{mol}	Temperature of the molasses	ºC
T_{steam}	Temperature of the condensing steam	ºC
T_{sat}	Temperature of the saturated vapour produced by boiling	ºC
T_{sug}	Temperature of sugar	ºC
T_{wall}	Temperature of the tube wall	ºC
u_{liq}	Superficial liquid phase velocity	$m.s^{-1}$
$\bar{u}_{liq}$	Average liquid phase velocity	$m.s^{-1}$
u_{TP}	Two-phase velocity of the liquid-vapour mixture	$m.s^{-1}$
u_{vap}	Superficial vapour phase velocity	$m.s^{-1}$
$\bar{u}_{vap}$	Average vapour phase velocity	$m.s^{-1}$
U	Overall heat transfer coefficient	$W.m^{-2}.K^{-1}$
V_{fluid}	Velocity of the fluid perpendicular to the probe	$m.s^{-1}$
V_{liq}	Mean velocity of the fluid entering the tube	$m.s^{-1}$
V_r	Mean bubble rising velocity	$m.s^{-1}$
x	Mixture quality	-
z	Length along the heated tube	m

Greek letters

α	Vapour volume fraction	-
α_{dif}	Thermal diffusivity	$m^2.s^{-1}$
∂_t	Thermal boundary layer thickness	m
ΔT	Temperature difference between the tube wall and liquid	ºC

ΔT_{eff}	Effective temperature difference	K
γ	Shear rate	s^{-1}
γ_{corr}	Corrected shear rate	s^{-1}
λ_{fg}	Latent heat of condensation of the steam	$J.kg^{-1}$
$\lambda_{fg,liq}$	Latent heat of the sugar solution	$J.kg^{-1}$
ρ_{liq}	Density of the liquid	$kg.m^{-3}$
ρ_{mass}	Density of the massecuite	$kg.m^{-3}$
ρ_{mol}	Density of the molasses	$kg.m^{-3}$
ρ_{mix}	Density of the process fluid in the heated tube	$kg.m^{-3}$
ρ_{vap}	Density of saturated water vapour	$kg.m^{-3}$
ρ_{xal}	Density of the crystal	$kg.m^{-3}$
μ_{liq}	Dynamic viscosity of the liquid	Pa.s
μ_{mass}	Dynamic viscosity of the massecuite	Pa.s
μ_{mol}	Dynamic viscosity of the mother molasses	Pa.s
σ_{liq}	Surface tension of sugar solution	$N.m^{-2}$
σ_{mol}	Surface tension of mother molasses	$N.m^{-2}$
τ	True shear stress	$N.m^{-2}$

Subscripts

liq	Liquid component of solution
vap	Vapour component of solution
mass	Massecuite
mol	Molasses
sug	Sugar