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INSTANT MILK POWDER PRODUCTION: DETERMINING THE EXTENT OF AGGLOMERATION

A thesis presented in partial fulfilment of the requirements for the degree of

Doctor of Philosophy
in
Chemical Technology

at Massey University, Palmerston North,
New Zealand.

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2007

ABSTRACT

Agglomerated milk powders are produced to give improved properties such as flowability, dispersibility, reduced dustiness and decreased bulk density. A key function of these powders is to dissolve "instantly" upon addition to water and because of this they are also called "instant milk powders". They are produced by agglomerating the undersized fines that are returned to the top of the spray drier with milk concentrate droplet spray. Interaction occurs in a collision zone, often with multiple sprays and fines return lines. Agglomeration can be a difficult process to control and operators find it hard to fine tune the process to produce specific powder properties. This work aimed to understand the effects of key droplet and fines properties on the extent of agglomeration to allow a mechanistic understanding of the process.

Three scales of spray drier were investigated in this study with different rates of evaporation; a small scale drier (0.5 – 7 kg water h^{-1}), a pilot scale drier (80 kg water h^{-1}) and a range of commercial production scale driers (4 - 15 000 kg water h^{-1}). A survey of operators of commercial scale driers showed that control of instant milk powder production to influence bulk density is highly intuitive. Fines recycle rates were expected to be important in control of agglomeration processes and were estimated on a specific plant by using the pressure drop measured in the fines return line. A model based on pressure drop along a pneumatic pipeline under-predicted the experimental values for pressure drop due to solids, which means a calibration curve should be generated for each specific drier. Fines recycle rates were predicted to be significantly higher at 95 to 130 % of production rates compared to those expected by operators of 50%.

Experimental measurements agreed with existing models for the effect of temperature on the density and viscosity of milk concentrates. Experimental results showed that the surface tensions of concentrated milks were within the same range as literature values for standard milks below 60°C, but were significantly higher for milk above 60°C. This is thought to be linked to the mechanism of skin formation due to disulphide cross linking at high temperatures and concentrations. Powder properties were also established for selected products produced on the commercial scale driers. These powders were then used in experiments on the two smaller driers. Because collision frequency depends on the velocity and droplet size of sprays; these properties were measured for the small scale drier and estimated, where possible, for the pilot and commercial driers.

The small scale agglomerating spray drier was configured to alter droplet and particle properties when interacting a vertical fines particle curtain with a horizontal spray sheet. An extensive design and improvement process was carried out to ensure the system consistently delivered these streams in a controllable manner. The processes of collision and adhesion occur very quickly inside the spray drier. In order to assess the extent of agglomeration that has occurred, the feed streams must be compared to the final product stream. An ideal way to do this is to use an agglomeration index which compares the particle size distributions of the feed (fines recycle and spray streams) and the particle size distribution of the product stream (the agglomerated powder). The index described changes between these steams across the particle size distribution and is called an agglomeration efficiency, ξ_g. However, it was found that the presence of fines in the product of the one-pass design obscured the agglomerates formed. The agglomeration efficiency, ξ_g, was modified to become ξ_h which subtracted the fines stream from the agglomerated product distribution. In this way ξ_h models industrial operation where the fines are recycled, by effectively just comparing the spray and product streams entering and leaving the process.

The small scale drier was used for an experimental study on natural and forced agglomeration, where the drier was operated with spray only, then with spray and fines. For natural agglomeration, SEM images of the product powder indicated that little agglomeration occurred between spray droplets. The product yield was unacceptably low (~ 40%) due to adhesion of spray droplets to the drying chamber wall opposing the horizontal spray. When the fines curtain was introduced in the forced agglomeration experiments, product yield increased above 50% because the fines acted as collectors for the spray droplets. However, the agglomeration performance of the modified spray drier was lower than expected. The equipment design was then optimised by considering three key issues; fines dispersion, droplet dispersion and stickiness, and agglomerate breakdown. Final experiments studied agglomeration at low fines to spray mass flux ratios and showed that increasing the fines size had a positive effect on agglomeration efficiency, ξ_h.

The agglomeration study at pilot scale identified the effect of key variables, total solids, concentrate and fines flow rate, and fines size on the agglomeration efficiency. A dimensionless flux approach was used to explain the experimental results. The fines to spray mass flux ratio and the projected area flux ratio (at constant concentrate flow rate) were found to be the most suitable to represent the physical processes during agglomeration. Experimental results showed that a higher dimensionless flux resulted in more agglomeration and as well as small fines size and atomising low solids concentrate. The critical Stokes number highlighted the importance of particle size and collision velocity on the outcome of the collision as well as the importance of stickiness on adherence following the collision. A statistical analysis established a relational model for predicting the agglomeration efficiency based on fines size, total solids and the fines to spray mass flux ratio.

This thesis has gained insight into agglomeration processes during spray drying and knowledge about how to define the extent of agglomeration. Practical findings from this research can have a significant impact on successful spray drying operation for instant powders. There are some practical steps to be taken industrially to promote the control of agglomerating spray driers. The first step is to measure and control the flow of fines recycled to the top of the spray drier. The next step is to validate the findings at industrial scale and link the agglomeration index to the bulk powder properties. However, there are many challenges that remain to be tackled in the area of milk powder agglomeration. Milk powder agglomeration at the top of the spray drier is a complex process involving many different variables. A more detailed study of the micro processes that occur during agglomeration will give increased understanding of the relationships between key operating variables and agglomerate properties.

ACKNOWLEDGEMENTS

"Particles can't read" so just writing the word agglomeration on a piece of equipment will not necessarily ensure this is the process that will happen inside. This quote certainly sums up my thesis, which would have told quite a different story if only particles could read.

A PhD is a rollercoaster ride of success and failure, however this journey is never completed alone. There are many people who deserve to be thanked for the part they have played along the way. Of course, I would like to thank all of my supervisors for their contributions; your discussions, guidance and patience was appreciated.

Firstly, thanks to my primary supervisor Dr. Jim Jones, for convincing me to do this project and for helping me seize opportunities. I have truly valued the support, advice and encouragement that you have given me. Also thanks go to Associate Professor Tony Paterson for your enthusiasm and general support and for challenging my ideas. Finally to my industry supervisor Dr. David Pearce, thank you for all of your assistance and practical advice; it was invaluable.

Special thanks to Associate Professor John Abrahamson and Mr Trevor Berry from the University of Canterbury for their assistance with the high speed camera for capturing the size and velocity of sprays.

Thanks to the staff in the Institute of Technology and Engineering at Massey University. I am also grateful for the other postgraduate students who helped me survive the process, especially Adi, Amsha, Craig, Jarod, Jeremy, Jenny, Kelly, Rachel, Ros, and Stephen.

There are so many people at Fonterra Palmerston North that I would like to thank for their help and assistance in this project whether it was in the lab, for strange requests or just general friendliness. Thank you all: Amy Yang, Brenda Bowie, Giao Truong, Skelte Anema, Marcel Hollenstein, Robyn Hirst, Liz Nickless, and Barabara Kuhn-Sherlock. Special thanks to Colin Knight for his helpful ideas, kiwi ingenuity and No. 8 wire. Also thanks to Susan Adams, John Grant, Dennis Dugmore and Bill Barnes for their time and humour. At Fonterra Whareroa, thanks to Jason Stevenson and Daniel Parker for their assistance.

I am grateful for the support of my friends and family (the Williams' and the Young's) throughout this project; I certainly could not have done it without you all. Special thanks to my parents and sisters for giving me your love, support and encouragement. Last but not least, thanks to Glen, without your love and understanding, this would not have been possible, thank you for your unconditional support.

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NOMENCLATURE

$\dot{A}$	area flux of powder traversing the spay zone	$m^2\ s^{-1}$
A	area	m^2
A_t	total cross sectional nozzle area	m^2
A_p	particle surface area	m^2
A_{spray}	spray on foot print area of the nozzle onto the powder bed	m^2
Ca	Capillary number	–
C_D	drag coefficient of particle	–
$C_D{}'$	modified drag coefficient	–
C_p	specific heat capacity at constant pressure	$J\ kg^{-1}\ K^{-1}$
D	diameter	m
D_0	initial droplet diameter	m
D_{12}	sum of colliding particle radii	m
$D_{3,2}$	Sauter mean diameter	m
$D_{4,3}$	volume weighted mean diameter	m
D_{BET}	BET diameter	m
D_{bridge}	diameter of sinter bridge	m
D_f	diffusion coefficient	$W\ m^{-1}\ K^{-1}$
D_{max}	maximum diameter of droplet	m
DoA	degree of agglomeration	–
$D_{particles}$	volume mean particle diameter of the particles	m
$D_{primary}$	diameter of initial particles	m
D_v	diffusion coefficient of water vapour in air	$W\ m^{-1}\ K^{-1}$
D_w	diffusion coefficient of water vapour through the droplet	$W\ m^{-1}\ K^{-1}$
e	coefficient of restitution	–
E_{in}	heat in inlet air	kW
E_{loss}	heat loss	kW
E_{out}	heat in outlet air	kW
f	frequency	–
F	fines flow rate	$kg\ s^{-1}$
FN	flux number	–
f_n	number of fines particles	–
F_N	total number of fines particles	–
f_p	solids-pipe friction factor	–
F_{PA}	projected area of fines	m^2
F_{pw}	solids-pipe friction force	$Pa\ m^{-1}$
F_t	impact force	$Pa\ m^{-1}$
g	acceleration due to gravity	$m\ s^{-2}$
h	convective heat transfer coefficient	$W\ m^{-2}\ K^{-1}$
h_a	height of granule surface asperities	m
H_{amb}	enthalpy of ambient air	$kJ\ kg^{-1}$
H_{fus}	latent heat of fusion	$J\ kg^{-1}$
H_{in}	enthalpy of inlet air	$kJ\ kg^{-1}$

h_m	convective mass transfer coefficient	W m^{-2} K^{-1}
H_{out}	enthalpy of outlet air	kJ kg^{-1}
k	constant or ratio of specific heats	–
K	consistency coefficient	N s m^{-2}
KD	constant × particle diameter	M
KE_1	kinetic energy before impact	J
KE_2	kinetic energy after impact (droplet is at maximum	J
k_l	thermal conductivity of liquid	W m^{-1} K^{-1}
L	length	m
L_e	equivalent length	m
l_v	friction loss	m^2 s^{-2}
l_w	wetted length of Wilhelmy plate	m
m	mass loading = ratio of M_p to M_g	–
M_A	mass rate of air	kg s^{-1}
M_{atm}	mass flow rate of air through the atomiser	kg s^{-1}
M_c	mass flow rate of concentrate	kg s^{-1}
M_{chute}	mass flow rate of air through the chute	kg s^{-1}
M_f	mass flow rate of fines	kg s^{-1}
M_g	mass flow rate of gas	kg s^{-1}
M_{in}	mass flow rate of inlet air	kg s^{-1}
M_{leak}	mass flow rate of air in due to leakage	kg s^{-1}
m_{obs}	mass of powder added over observed time	kg
M_{obs}	mass flow rate of fines (observed)	kg s^{-1}
M_{out}	mass flow rate of outlet air	kg s^{-1}
M_p	mass flow rate of particles	kg s^{-1}
M_{prod}	mass flow rate of powder production	kg s^{-1}
M_s	mass flow rate of spray	kg s^{-1}
m_t	total mass added	kg
n	power law index	–
$\hat{N}$	number concentration of particles	m^{-3}
$\dot{N}$	number flow rate	s^{-1}
N	number of particles per kilogram	kg^{-1}
Nu	Nusselt number	–
Oh	Ohnesorge number	–
p	mass proportion in the powder	–
P_1	inlet nozzle pressure	Pa
P_2	exit nozzle pressure	
Pr	Prandlt number	–
P_w	Wilhelmy force	N
ΔP	pressure drop	Pa
ΔP_{fg}	pressure drop due to friction of gas	Pa
ΔP_{fs}	pressure drop due to solids friction	Pa
ΔP_g	pressure drop due to gas	Pa
Δp_{hug}	pressure drop due to hold up of gas	Pa

ΔP_{hus}	pressure drop due to hold up of solids	Pa
ΔP_s	pressure drop due to solids	Pa
Q_a	volumetric air rate	$m^3\ s^{-1}$
$Q_{a.c}$	volumetric flow rate of curtain air	$m^3\ s^{-1}$
Q_{atm}	volumetric flow rate of atomising air	$m^3\ s^{-1}$
q_b	binder spray rate	$kg\ s^{-1}$
Q_l	liquid flow rate	$kg\ s^{-2}$
r	particle or granule radius	µm
Re	Reynolds number	–
RH	relative humidity	$kg\ kg^{-1}$
S	spray flow rate	$kg\ s^{-1}$
Sc	Schmidt number	–
SE_1	the surface energy before impact	J
SE_2	surface energy after impact	J
S_g	geometric standard deviation	–
Sh	Sherwood number	–
s_n	number of spray droplets	
S_N	total number of spray droplets	–
S_{PA}	projected area of spray	m^2
SSA	specific surface area	$m^2\ g^{-1}$
St^*	critical Stokes' number	–
Ste	Stefan number	–
St_V	viscous Stokes' number	–
T	temperature	°C
T_{amb}	ambient temperature	°C
T_1	air temperature under sonic conditions	°C
t	time	s
t_{exp}	exposure time	s
T_g	glass transition temperature	°C
T_m	droplet melting temperature	°C
TS	total solids concentration	–
$T_{w,1}$	initial substrate temperature	°C
U	velocity	$m\ s^{-1}$
u_0	initial relative granule collision velocity	$cm\ s^{-1}$
U_0	droplet impact velocity	$m\ s^{-1}$
U_A	velocity of air	$m\ s^{-1}$
U_{A1}	predicted air exit velocity from the nozzle	$m\ s^{-1}$
U_{A2}	predicted velocity 50mm from nozzle of air and spray	$m\ s^{-1}$
$U_{air\ only}$	measured air velocity 50 mm from nozzle without spray	$m\ s^{-1}$
U_c	collision velocity	$m\ s^{-1}$
UD	constant, D and overall heat transfer coefficient U	$W\ K^{-1}$
U_d	droplet velocity	$m\ s^{-1}$
u_e	excess gas velocity	$m\ s^{-1}$
U_g	interstitial gas velocity	$m\ s^{-1}$

U_s	velocity of particles	m s^{-1}
U_T	terminal velocity	m s^{-1}
u_z	velocity of entrained air	m s^{-1}
$u_{zmax\infty}$	centre velocity of the air in the equilibrium state	m s^{-1}
$\dot{V}$	volumetric spray rate of the binder liquid	m^3 s^{-1}
v	specific volume of mixture	m^3 kg^{-1}
V_b^*	dimensionless bridge volume	–
V_b	pendular bridge volume	m^3
V_d	droplet volume	m^3
v_f	specific volume of fat	m^3 kg^{-1}
V_g	volume of gas	m^3
v_i	specific volume of component i	m^3 kg^{-1}
v_{nw}	specific volume of native whey protein	m^3 kg^{-1}
v_{rel}	relative velocity between liquid and air	m s^{-1}
V_s	volume of solids	m^3
v_s	velocity of a single particle	m s^{-1}
$v_{s\infty}$	terminal velocity of a single particle	m s^{-1}
v_z	velocity of the particle in the powder jet	m s^{-1}
v_{zmax} *infin*	centre velocity of the particle in the equilibrium state	m s^{-1}
w	width	m
W^*	dimensionless rupture energy	–
W	pendular bridge rupture energy	J
We	Weber number	–
W_{vis}	work done in deforming a droplet against viscosity	J
x	curtain width	m
X_c	dry matter content of concentrate	kg kg^{-1}
X_{casein}	mass concentration of casein	kg L^{-1}
X_{dw}	mass concentration of denatured whey protein	kg L^{-1}
X_{eq}	equilibrium moisture content	kg kg^{-1}
X_{fat}	percentage of fat	–
x_i	percentage of component i in the mixture	–
x_l	dry matter fraction of lactose	kg kg^{-1}
X_{milk}	dry matter content of standard milk	kg kg^{-1}
X_{nw}	mass concentration of native whey protein	kg L^{-1}
y	curtain length	m
Y_g	dynamic yield stress	Pa
Z_{12}	collision rate between two particles	m^{-3} s^{-1}

Greek Letters

μ	viscosity	Pa s
μ_g	viscosity at the glass transition temperature	Pa s
μ_l	viscosity of lactose solution	Pa s
μ_{ref}	viscosity of the serum	Pa s
α	shape factor	–

γ	rate of strain	s^{-1}
ε	voidage	–
θ	contact angle	°
θ_a	advancing contact angle	°
ξ_g	agglomeration efficiency using *g* distribution	–
ξ_h	agglomeration efficiency using *h* distribution	–
ρ	density	kg m^{-3}
σ	surface tension	N m^{-1}
σ_l	surface tension of saturated lactose	N m^{-1}
τ	shear stress	Pa
Φ	volume fraction of concentrate	–
Φ_{max}	the maximum volume fraction	–
Φ_{milk}	volume fraction of milk	–
ψ	dimensionless time	–
Ψ_a	dimensionless spray flux	–
δ	thickness of the liquid layer	m

Subscripts

0	before
1	after
a	air
agg	agglomerates
c	concentrate
d	droplet
AE	entrained air
f	fines
g	gas
p	particle or product
s	spray, dried droplets
skim	skim milk
whole	whole milk

Acronyms

AF	agglomeration factor
AP	agglomeration parameter
BET	Brunauer, Emmett, & Teller
DoA	degree of agglomeration
GAB	Guggenheim-Anderson-de Boer
ISMP	instant skim milk powder
IWMP	instant whole milk powder
PSD	particle size distribution
SEM	scanning electron microscopy
SMC	skim milk concentrate
SSA	specific surface area
SSM	standard skim milk
SWM	standard whole milk
WMC	whole milk concentrate