ASPECTS OF FOULING IN DAIRY PROCESSING

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ABSTRACT

Fouling of heat treatment equipment in the dairy processing industry is an expensive and persistent problem. The objective of this work was to develop a better understanding of the mechanisms of dairy fouling in heat exchangers and identify methods to control this build-up. This was part of a larger project investigating the interaction between spore-forming thermophilic bacilli (thermophiles) contamination and fouling deposits on internal surfaces of equipment.

Two systems were developed to monitor the onset and build-up of fouling on the internal surfaces of two research heat exchangers. The first used a commercial sensor to measure the local heat flux and the temperature on the hot side of a plate type heat exchanger. The heat transfer coefficient was calculated and normalised with its value at the start of the run to reflect the contribution of fouling deposits to the thermal resistance, thus giving a real-time estimate of the rate of fouling. The second system used an energy balance over a tubular type heat exchanger and measured inlet and outlet temperatures to estimate the overall heat transfer coefficient thus giving a global measurement of fouling over the tubular heat exchanger.

In both systems the plot of normalised heat transfer coefficient over time often stayed constant over an induction period, which was followed by a falling period indicative of growth in the fouling layer thickness and/or mass. Each system was validated by comparing the final value of the normalised heat transfer coefficient with direct measurements of fouling made at the end of a run namely: fouling deposit height for the local measurement and fouling deposit mass for the global measurement. The normalised heat transfer coefficient reported by each system correlated well with the corresponding direct measurement of the fouling layer.

An important factor identified in this study was the effect of air bubble nucleation on fouling deposits. It was shown that bubbles that formed on the heated surface greatly reduced the length of the induction period to a matter of seconds rather than hours, as found in previous studies of fouling in the absence of surface bubbles. The rate of fouling was also enhanced while the bubbles remained at the surface. The structure of bubble type fouling layers was linked to the behaviour of the bubbles at the heated surface. Visual observations of these bubbles showed evidence of growth, vibration and coalescence during their period of attachment to the heated surface.

Deposits from bubble type fouling consisted of all solid components found in the original milk solution, except lactose, in approximately the same ratio. By contrast fouling deposits reported in the literature with systems operating under the traditional protein denaturation mechanism were reported to consist mainly of whey proteins.

Bubble induced fouling can be limited in a number of ways, the most effective being to maintain a high operating pressure in the equipment to ensure nucleation does not occur. Experiments conducted in this study showed that a pressure of 130 kPa.g was sufficient to suppress all bubble nucleation at the heated surface at a temperature of 90°C.

Another method identified was the use of high linear fluid velocities to entrain any surface bubbles into the processing stream immediately upon nucleation. Linear velocities above 1.0 m/s were shown to achieve this goal in the miniature plate heat exchanger tested. However, this method is only partially successful because the local linear velocity varies with position in heat exchange equipment of complex geometries and can drop below the mainstream average velocity causing surface bubbles to form, especially in recirculation regions behind flow obstacles.

A more reliable method, in situations where high operating pressures could not be used, involved conditioning the heated surface with a thin protein layer during the first few minutes of a run. Conditioning the surface resulted in bubble suppression even at high temperatures and low pressures, thus greatly extending the length of the induction period.

Trials performed in this study showed that the addition of a proteolytic enzyme produced by psychrotrophic microbes greatly increased fouling. The enzyme destabilised the caseins which could attach directly to the heat exchange surface independently from the bubble fouling mechanism. Thus the quality of the milk is another important factor to consider. However, the addition of enzymes produced by thermophilic bacilli isolated from milk powder plants did not increase fouling.

A theory describing the air bubble induced fouling mechanism is presented along with recommendations on how to reduce this fouling contamination in processing equipment.

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TABLE OF CONTENTS

ABSTRACT **ii**
ACKNOWLEDGEMENTS **v**
TABLE OF CONTENTS **vi**
LIST OF FIGURES **x**
LIST OF TABLES **xvi**
NOMENCLATURE **xviii**
INTRODUCTION **1**
1.1 OBJECTIVES 2
LITERATURE REVIEW **4**
2.1 INTRODUCTION 4
2.2 FOULING DURING DAIRY PROCESSING 4
2.2.1 Milk 5
2.2.2 Heat treatment 6
2.2.3 Phases of fouling 8
2.2.4 Composition 9
2.2.5 Microstructure 13
2.2.6 Fouling mechanisms 14
2.2.6.1 Induction layer 15
2.2.6.2 Rate determining step 15
2.2.6.3 Activation and transport of depositing species 16
2.2.7 Factors affecting fouling 20
2.2.7.1 Milk pH 20
2.2.7.2 Milk age 21
2.2.7.3 Seasonal variation 22
2.2.7.4 Milk preheating 23
2.2.7.5 Dissolved gases 23
2.2.7.6 Surface condition 26
2.2.7.7 Flow velocity 27
2.2.7.8 Equipment geometry 28
2.3 EXPERIMENTAL SETUPS FOR FOULING INVESTIGATIONS 28

2.3.1 Test fluid 29
2.3.2 Equipment 30
2.3.3 Measurements of fouling 33
2.3.3.1 Direct 33
2.3.3.2 Indirect 34
2.3.3.3 Local fouling measurements 37
2.4 CONCLUSION 39
MATERIALS AND METHODS **40**
3.1 INTRODUCTION 40
3.2 PILOT PLANT 40
3.2.1 Preheating 43
3.2.1.1 Miniature plate heat exchanger (MPHE) rig 43
3.2.1.2 Tubular heat exchanger (THE) rig 46
3.2.2 Instrumentation and data acquisition 48
3.2.2.1 Control room and data acquisition 48
3.2.2.2 Temperature measurement 49
3.2.2.3 Flow rate measurement 50
3.2.2.4 Pressure measurement 51
3.2.3 Operating procedures 51
3.2.3.1 Plant preparation 52
3.2.3.2 Start up protocol 52
3.2.3.3 Run protocol 53
3.2.3.4 Clean In Place (CIP) protocol 53
3.2.3.5 Shut-down protocol 54
3.3 METHODS OF MEASUREMENT AND ANALYSIS 54
3.3.1 Direct fouling measurement 54
3.3.1.1 Mass 54
3.3.1.2 Thickness 55
3.3.1.3 Photography 56
3.3.2 Indirect fouling monitoring 60
3.3.2.1 Theory 60
3.3.2.2 Local measurement of fouling 61
3.3.2.3 Global measurement of fouling 66
3.3.2.4 Calculations from fouling curves 67
3.3.3 Chemical procedures 69

3.3.3.1 Enzyme 69
3.3.3.2 Composition 70
3.4 OVERVIEW OF EXPERIMENTAL PROGRAM 71
RESULTS 72
4.1 INTRODUCTION 72
4.2 FOULING OF HEATED SURFACES BY MILK 73
4.2.1 Characteristics of fouling curves 73
4.2.2 Reproducibility 78
4.2.3 Relation between direct and indirect methods of fouling measurement 80
4.2.4 Enzymatic damage 83
4.2.4.1 Combined effect of temperature and Neutrase addition on fouling 89
4.3 INFLUENCE OF BUBBLE NUCLEATION ON FOULING 95
4.3.1 Fouling and bubble nucleation 95
4.3.2 Process variables and geometry 104
4.3.2.1 Pressure 104
4.3.2.2 Flow rate 117
4.3.2.3 Geometry 121
4.3.3 Influence of start up procedure on fouling 125
4.3.3.1 Dry start versus wet start 125
4.3.3.2 Delayed heating 127
4.3.3.3 Validation 132
4.3.3.4 Surface coatings 135
DISCUSSION 138
5.1 PROTOCOL OF FOULING RUNS AND METHODS OF MEASUREMENT 138
5.2 DISCUSSION OF RESULTS OF FOULING RUNS 141
5.3 MECHANISMS OF FOULING WITH SPECIAL REFERENCE TO BUBBLES 146
CONCLUSIONS AND RECOMMENDATIONS 155
REFERENCES 157
Appendix A OVERVIEW OF EQUIPMENT AND MATERIALS A1
APPENDIX A.1 Detailed information on selected equipment A14
Appendix B OPERATING PROTOCOL A16
Appendix C SUMMARY OF EXPERIMENTAL RUNS A21
Appendix D SAMPLE CALCULATIONS A26
APPENDIX D.1 Calibration constants for temperature sensors A26
APPENDIX D.2 Calibration of heat flux sensors A27

APPENDIX D.3 Fouling monitoring systems A28

APPENDIX D.4 Fouling curves A37

APPENDIX D.5 Product linear velocity of an industrial heat exchanger A39

Appendix E SIGMASCAN METHODOLOGIES A40

Appendix F MATERIAL PROPERTIES A46

APPENDIX F.1 Neutrase A46

APPENDIX F.2 Whey Protein Concentrate A47

APPENDIX F.3 Milk A47

Appendix G CHEMICAL METHODOLOGIES A49

APPENDIX G.1 Moisture analysis A49

APPENDIX G.2 Ash analysis A50

APPENDIX G.3 Protein analysis A50

APPENDIX G.4 Fat analysis A51

APPENDIX G.5 Reducing SDS-PAGE analysis procedure A53

Appendix H DATA DISK A56

LIST OF FIGURES

Figure 2.1 Idealised fouling curves (Fryer *et al.*, 1995). 8

Figure 2.2 Diagrammatic representation of fouling distribution in an indirect heat exchanger operating on raw milk (Burton, 1988). 10

Figure 2.3 Scanning electron micrograph of Type A deposit structure (a) stainless steel surface (b) sub-layer (c) top-layer (Truong, 2001). 14

Figure 2.4 Schematic representation of the fouling mechanisms during the heating of whey and milk (Jeurnink *et al.*, 1996c). 17

Figure 2.5 Air bubble formed at a heated surface and processes occurring near it. See text for explanation. Highly schematic and not to scale (Walstra *et al.*, 1999). 25

Figure 2.6 Schematic representation of the participation of an air bubble in the fouling process of milk (1) adsorption/deposition at the vapour/liquid interface (2) evaporation (3) condensation (Jeurnink, 1995a). 26

Figure 3.1 Schematic diagram of pilot plant depicting standard set up of process fluid flow. 41

Figure 3.2 Photograph of the pilot plant showing preheating (right) and evaporator (left) sections. 42

Figure 3.3 A three-dimensional representation of a module developed for the study of fouling and bacterial contamination. 44

Figure 3.4 Photograph of the miniature plate heat exchanger rig. 45

Figure 3.5 Photograph of the tubular heat exchanger rig. 47

Figure 3.6 The assembly of an individual tubular heat exchanger. 47

Figure 3.7 Pilot plant control room and cabinet showing PLC (right). 48

Figure 3.8 Photograph of the deposit thickness measuring device (a) plate support (b) dial depth gauge (c) multimeter. 55

Figure 3.9 Photograph of the modified MPHE showing transparent Perspex section. 57

Figure 3.10 Sigmascan Pro Image Analysis software showing the original image (a) and the analysed image including the measurement output (b). Note: the blue overlay indicates the areas of fouling and the green overlay indicates the area outside the heat exchange surface (not measured). 59

Figure 3.11 Schematic drawing of the sectional view of a fouled surface showing the thermal resistances across the heat exchanger. 61
Figure 3.12 Photograph of a thin-foil heat flux sensor. 62
Figure 3.13 Heat flux sensor attached to a MPHE plate. 63
Figure 3.14 Schematic diagram of the local fouling monitoring equipment implemented in the MPHE rig. 65
Figure 3.15 Schematic diagram of the global fouling monitoring equipment implemented in the THE rig. 67
Figure 3.16 Plot of N_f versus run time showing the method used to calculate the fouling rate (R1.4). 68
Figure 4.1 Intermediate process data for R2.1. 73
Figure 4.2 Calculated internal heat transfer coefficient versus run time for R2.1. 74
Figure 4.3 Intermediate process data for R1.18. 75
Figure 4.4 Calculated overall heat transfer coefficient versus run time for R1.18. 75
Figure 4.5 Comparisons of N_f calculated from the local and global systems. 76
Figure 4.6 N_f versus run time for R1.4 showing induction and fouling periods. 77
Figure 4.7 N_f versus run time for R2.2 showing no fouling period. 77
Figure 4.8 N_f versus run time for R1.22 showing two distinct fouling rates. 78
Figure 4.9 N_f versus run time for the 30 kPa.g replicate runs (R1.1-1.3). 80
Figure 4.10 N_f versus run time for the local system's validation experiment (R2.3). 81
Figure 4.11 Relationship between the N_f and the average deposit thickness of fouling both measured at module isolation (R2.3). 82
Figure 4.12 Relationship between N_f and the mass of dry foulant both measured at the end of each run. 83
Figure 4.13 The mass of dry foulant measured at the end of each run using the THE processing whole milk with (R1.10, R1.11) and without (R1.17, R1.18) the addition of bacterial enzymes. 84
Figure 4.14 Reducing SDS-PAGE of liquid whole milk (A) with addition of extracellular enzymes of *B. stearothermophilus* (B12 Cm) after 1 (B), 3 (C) and 5 (D) hour incubation periods at 4°C. 85
Figure 4.15 Reducing SDS-PAGE of liquid whole milk (A) with the addition of protease enzymes of *B. amyloliquefaciens* (Neutrase) after 1 (B), 3 (C) and 5 (D) hour incubation periods at 4°C. 86
Figure 4.16 Reducing SDS-PAGE of deposit formed by heating milk: (A) liquid whole milk (B) deposit of whole milk (*B. amyloliquefaciens* control – R1.18) (C) deposit

of whole milk after incubation with protease enzymes of *B. amyloliquefaciens* (Neutrase – R1.11) (D) deposit of whole milk (*B. stearothermophilus* control – R1.17) (E) deposit of whole milk after incubation with extracellular enzymes of *B. stearothermophilus* (B12 Cm) – R1.10 (F) protein broad band standard. 88

Figure 4.17 The effect of heating surface temperature on the mass of dry foulant obtained at the end of each run using the THE processing whole milk with and without the addition of protease enzymes of *B. amyloliquefaciens* (Neutrase). 90

Figure 4.18 The effect of THE surface temperature on the rate of fouling of whole milk with and without the addition of protease enzymes of *B. amyloliquefaciens* (Neutrase). 92

Figure 4.19 Example structure of fouling formed in the THE processing whole milk at 88°C (R1.18). 94

Figure 4.20 Example structure of fouling formed in the THE processing of Neutrase modified whole milk at 88°C (R1.11). Note how the craters have been filled to leave a relatively smooth outer surface. 94

Figure 4.21 Example structure of fouling formed in the THE processing of Neutrase modified whole milk at 88°C (R1.11). Note milk solids appear to deposit directly onto the stainless steel surface as well as the porous structure. 94

Figure 4.22 Results of the bubble-fouling linkage trial: (a, b) R2.4; (c, d) R2.5; (e, f) R2.6. (a, c, e) Video stills showing the bubble formation on the heated surfaces. (b, d, f) Photographs of the test plates taken after each run showing the fouling pattern. 96

Figure 4.23 Video stills showing the bubble pattern on the MPHE heated surface processing a WPC solution at 502 l/h over the first five minutes of the run (R2.6). 99

Figure 4.24 The section of the test plate from R2.6 used to make additional observations of bubble-type fouling structures. 101

Figure 4.25 Video stills showing bubble nucleation over time in the area selected to make additional observations of the surface during and after the 50 minute run (R2.6). 101

Figure 4.26 Magnified image (20 X) of the test plate fouled with a WPC solution showing evidence of bubble movement over the surface (R2.6). 102

Figure 4.27 WPC fouling showing different types of structures: (a) stationary R2.9 (b) anchor R2.20 (c) shell-like R2.7 (d) coalescence R2.9. All runs processed at 45 l/h. 103

Figure 4.28 The effect of the process side operating pressure on the mass of dry foulant obtained at the end of each run using the THE processing whole milk. 105

Figure 4.29 The effect of THE process side operating pressure on the rate of fouling of whole milk. 105

Figure 4.30 An example structure of the fouling obtained after processing whole milk in the THE at an operating pressure of 30 kPa.g (R1.1). 106

Figure 4.31 An example structure of the fouling obtained after processing whole milk in the THE at an operating pressure of 80 kPa.g (R1.9). 106

Figure 4.32 Analysed image of Figure 4.30. Red regions indicate the areas of the tube not covered in fouling. 107

Figure 4.33 Analysed image of Figure 4.31. Red regions indicate the areas of the tube not covered in fouling. 107

Figure 4.34 The effect of THE process side operating pressure on the area of the heated surface covered in whole milk fouling. 108

Figure 4.35 Mass of dry foulant obtained at the end of each run versus the area of the heated surface covered in whole milk fouling. 108

Figure 4.36 Expanded photograph of Figure 4.30 indicating the height of fouling above the horizon. Darkened section indicates the area of the THE tube (R1.1). 110

Figure 4.37 Expanded photograph of Figure 4.31 indicating the height of fouling above the horizon. Darkened section indicates the area of the THE tube (R1.9). 110

Figure 4.38 The effect of THE process side operating pressure on the foulant loading of whole milk on the heated surface. 110

Figure 4.39 Video stills showing the effect of operating pressure on bubble behaviour on the MPHE heated surface processing water. 112

Figure 4.40 The number of bubbles in a 25 mm^2 section of the heat exchange surface installed in the MPHE processing water at different pressures. 113

Figure 4.41 The average area of bubbles in a 25 mm^2 section of the heat exchange surface installed in the MPHE processing water at different pressures. 113

Figure 4.42 Video stills showing the effect of operating pressure on the bubble behaviour on the MPHE heated surface processing WPC solutions. 115

Figure 4.43 Topography of MPHE test plates after processing WPC solutions at different operating pressures (a) R2.4 (b) R2.7 (c) R2.5. 116

Figure 4.44 Video stills showing the effect of flow rate on bubble behaviour on the MPHE heated surface processing water. 118

Figure 4.45 Video stills showing the effect of flow rate on bubble behaviour on the MPHE heated surface processing WPC solutions. 119

Figure 4.46 Topography of MPHE test plates after processing WPC solutions at different process fluid flow rates (a) 45 l/h - R2.4 (b) 502 l/h - R2.6 (c) 1 940 l/h - R2.8. 120

Figure 4.47 Video stills showing the effect of an obstruction on bubble behaviour on the MPHE heated surface processing water. 122

Figure 4.48 Topography of MPHE test plates with glue drops attached after processing WPC solution at 46 l/h and 131 kPa.g. (R2.17) (a) module 1 (b) module 2 (c) module 4 (d) module 5 (e) module 6 [(a) – (e) 5 replicates]. 124

Figure 4.49 Video stills showing the effect of dry and wet starts on bubble behaviour on the MPHE heated surface processing water. 126

Figure 4.50 Video stills showing the effect of SCOP and non-SCOP starts on bubble behaviour on the MPHE heated surface processing water. 128

Figure 4.51 Video stills showing the effect of SCOP and non-SCOP starts on bubble behaviour on the MPHE heated surface processing WPC solutions. 129

Figure 4.52 Topography of MPHE test plates after processing WPC solutions with different start up procedures (a) non-SCOP - R2.4 (b) SCOP - R2.20. 130

Figure 4.53 N_f versus time for different start up procedures used with the MPHE processing whole milk: modules 1 & 3 (SCOP), modules 2 &4 (non-SCOP). 131

Figure 4.54 Topography of MPHE test plates after processing whole milk with different start up procedures R2.21 (a) module 1 SCOP 20 min (b) module 2 non-SCOP 20 min (c) module 3 SCOP 9.3 h (d) module 4 non-SCOP 9.3 h. 131

Figure 4.55 Topography of MPHE test plates after processing whole milk with different start up procedures R2.22 (a) module 1 non-SCOP (b) module 2 SCOP 5 seconds delay (c) module 3 SCOP 10 minutes delay (d) module 4 SCOP 20 minutes delay (e) module 5 SCOP 40 minutes delay (f) module 6 SCOP 60 minutes delay. 133

Figure 4.56 Topography of MPHE test plates after processing whole milk with and without Neutrase addition with different start up procedures R2.23 (a) module 1 whole milk non-SCOP (b) module 2 whole milk SCOP (c) module 3 Neutrase treated whole milk non-SCOP (d) module 4 Neutrase treated whole milk SCOP. 134

Figure 4.57 The effect of dipping the test plates in various treatments for 30 minutes on the mass of dry foulant produced in the MPHE rig when a solution of WPC was processed (R2.24). Dipping solutions: module 1 – none, module 2 - β-Lg, module 3 - α-La, module 4 – casein, module 5 - calcium phosphate, module 6 – lactose. 136

Figure 4.58 Topography of MPHE test plates dipped in solutions for 30 minutes before processing a WPC solution in the MPHE rig (a) module 1 none (b) module 2 β-Lg (c) module 3 α-La (d) module 4 casein (e) module 5 calcium phosphate (f) module 6 lactose. 137

APPENDICES A1

Figure A.1 Drawing A1 Preheating section P&ID A8

Figure A.2 Drawing A2 Miniature plate heat exchanger rig P&ID A9

Figure A.3 Drawing A3 Tubular heat exchanger rig P&ID A10

Figure A.4 Drawing A4 Direct steam injector dimension drawing A11

Figure A.5 Drawing A5 Miniature plate heat exchanger dimension drawing A12

Figure A.6 Drawing A6 Tubular heat exchanger dimension drawing A13

Figure A.7 Schematic diagram of a direct steam injection (DSI) unit. A14

Figure D.1 N_f versus run time for R1.9. A37

Figure E.1 Screen shots of Sigmascan when used to calculate the heat exchange surface area covered in fouling: (a) raw non-manipulated image (b) manipulated image with overlays applied and results worksheet showing a sample of raw and calculated data. A41

Figure E.2 Screen shots of Sigmascan when used to estimate the average size and number of bubbles in a 25 mm^2 sector: (a) raw non-manipulated image (b) image with grid overlay and bubble shape traced and counted. A43

Figure E.3 Screen shot of Sigmascan when used to assist in the quantification of proteins from electrophoresis gels. A44

Figure E.4 Screen shot of Sigmascan showing a macro used in automating the image analysis process. A45

LIST OF TABLES

Table 2.1 Typical composition of raw milk (Walstra *et al.*, 1999) 5

Table 2.2 Typical heating processes utilised in the dairy industry 7

Table 2.3 Composition of fouling layers from a selection of studies. 11

Table 2.4 Detailed protein composition of fouling deposits (Tissier *et al.*, 1984) 13

Table 3.1 Overview of experimental program 71

Table 4.1 Mass of dry foulant obtained from surfaces installed in the THE rig after processing whole milk (replicate runs). 79

Table 4.2 Protein composition (percentage intensity) of liquid whole milk incubated with extracellular enzymes of *B. stearothermophilus* and protease enzymes of *B. amyloliquefaciens*. 87

Table 4.3 Selected protein composition (percentage intensity) of liquid whole milk and deposit formed during control and enzyme addition runs. 88

Table 4.4 The effect of heating surface temperature on the mass of dry foulant obtained at the end of each run using the THE processing whole milk with and without the addition of protease enzymes of *B. amyloliquefaciens* (Neutrase). 91

Table 4.5 The composition of fouling deposit sampled from the THE after processing whole milk with and without the addition of protease enzymes of *B. amyloliquefaciens* (Neutrase). Ash, fat and protein expressed as percentage w/w. Protein components expressed as normalised percent. 92

Table 4.6 Processing conditions of bubble-fouling linkage trial 95

Table 4.7 Mass of dry foulant and foulant loading on plates installed in the MPHE rig after processing WPC solutions at different flow rates and pressures. 97

Table 4.8 Mass of dry foulant and foulant loading on tubes installed in the THE rig after processing whole milk at different operating pressures. 109

Table 4.9 Mass of dry foulant and foulant loading on plates installed in the MPHE rig after processing WPC solutions at different pressures. 116

Table 4.10 Process variables of the runs conducted with the MPHE processing water at different flow rates. 117

Table 4.11 Process variables of the runs conducted with the MPHE processing WPC solutions at different flow rates. 117

Table 4.12 Mass of dry foulant and foulant loading on plates installed in the MPHE rig after processing WPC solutions at different flow rates. 121

Table 4.13 Mass of dry foulant and foulant loading on plates installed in the MPHE rig after processing WPC solutions with different start up protocols (SCOP manipulation). 127

APPENDICES A1

Table A.1 List of pilot plant components. A2

Table A.2 List of measuring and optical equipment. A6

Table A.3 List of consumables used in the current project A7

Table C.1 Conditions of formal runs conducted with the THE rig. A21

Table C.2 Conditions of formal runs conducted with the MPHE rig. A22

Table C.3 Summary of commissioning and prerun trials conducted with the THE rig. A24

Table C.4 Summary of commissioning and prerun trials conducted with the MPHE rig. A25

Table D.1 Recorded calibration temperatures and calculated regression coefficients for selected temperature sensors installed in the pilot plant. A26

Table D.2 Manufacturer’s calibrated outputs for a selection of heat flux sensors installed in the pilot plant A27

Table D.3 Heat flux corresponding to the maximum voltage of 50mV and the factors used to convert the heat fluxes to SI units for a selection of heat flux sensors installed in the pilot plant A27

Table D.4 Sample of the MSExcel spreadsheet listing measured, estimated and calculated variables for R2.1 A29

Table D.5 Sample of the MSExcel spreadsheet listing process fluid constants and measured, estimated and calculated variables for R1.18 A33

Table D.6 Sample of the MSExcel spreadsheet showing the fouling rate calculation for R1.9. A38

Table D.7 Sample of the MSExcel spreadsheet showing the final N_f value estimation for R1.9. A38

NOMENCLATURE

Roman

a	gradient constant
A	surface area (m^2) or heat exchange surface area (m^2)
A_p	proteinase activity
b	y-axis intercept constant
c	constant
c_p	heat capacity of fluid (J/kg.K)
$c_{p,p}$	heat capacity of the process fluid (J/kg.K)
C_k	concentration of para-κ-casein
d_e	equal diameter of process fluid cross section (m)
d_i	inner diameter of inside tube (m)
d_o	outer diameter of inside tube (m)
D	hydraulic diameter (m)
D_0	hydraulic diameter at t=0 (m)
D_i	inner diameter of outside tube (m)
D_o	outer diameter of outside tube (m)
E	activation energy (J/mol)
f	friction coefficient
F	heat flux calibration factor (Wm^{-2}/binary unit)
k_a	rate constant
k_d	deposition rate constant (s^{-1})
L	length of pipe (m) or length of inner tube fouling region (m)
m	rate coefficient
$\dot{m}$	mass flow rate of fluid (kg/s)
N_f	normalised overall heat transfer coefficient
ΔP	differential pressure (Pa)
q	heat transfer flux (W/m^2)
Q	flow rate of process fluid (l/h) or (m^3/h)
R	total heat transfer resistance ($m^2.K/W$)
R_a	aluminium tape thermal resistance ($m^2.K/W$)

R_f	fouling thermal resistance (m^2.K/W)
R_g	universal gas constant (J/mol.K)
R_{hf}	heat flux sensor thermal resistance (m^2.K/W)
R_{hm}	heat medium thermal resistance (m^2.K/W)
R_p	process fluid thermal resistance (m^2.K/W)
R_{ss}	stainless steel wall thermal resistance (m^2.K/W)
R_w	wall and its attachment thermal resistance (m^2.K/W)
Ra	relative surface roughness (μm)
Re	Reynolds number = $dv\rho/\mu$ (dimensionless)
S	cross sectional area of process fluid (m^2)
T	solid-liquid interface temperature (°C)
U	heat transfer coefficient (W/m^2.K)
U_0	heat transfer coefficient at t=0 (W/m^2.K)
U_i	internal overall heat transfer coefficient (W/m^2.K)
U_{i0}	initial internal heat transfer coefficient (W/m^2.K)
v	flow velocity (m/s)
V	milk velocity (m/s)

Greek

α	fouling parameter
Φ	fouling rate (s^{-1})
$\Delta\theta$	temperature difference (°C)
$\Delta\theta_1$	temperature difference of side 1 (°C)
$\Delta\theta_2$	temperature difference of side 2 (°C)
$\Delta\theta_{LMTD}$	log mean temperature difference (°C)
$\Delta\theta_m$	mean temperature difference (°C)
θ_c	correct temperature (°C)
θ_{hf}	outer temperature of heat flux sensor (°C)
θ_{hm}	temperature of heating medium (°C)
θ_i	inlet temperature of test fluid (°C)
θ_o	outlet temperature of test fluid (°C)
θ_p	temperature of process fluid (°C)
θ_r	recorded temperature (°C)
Θ_{hm}	outlet temperature of the heating medium (°C)
Θ_p	outlet temperature of the process fluid (°C)

μ	dynamic fluid viscosity (kg/m.s)
μ_p	viscosity of process fluid (Pa.s)
ρ	density of fluid (kg/m^3)
ρ_p	density of process fluid (kg/m^3)
ϕ	heat transfer rate (W)
ϕ_{hm}	rate of heat lost by the heating medium (W)
ϕ_p	rate of heat gained by the process fluid (W)