Contents

List of Figures				
Lis	st of	Tables	xix	
Lis	List of Symbols			
1	Intro	oduction	1	
	1.1	Research Framework: advantages of slush	2	
	1.2	Slush production, characterization and transport: state of the art and		
		open questions	7	
		1.2.1 Slush production	7	
		1.2.2 Slush characterization: particles size and shape	8	
		1.2.3 Slush characterization: density and solid volume fraction	11	
		1.2.4 Slush transport features: pressure drop and heat transfer	14	
	1.3	Aims of the thesis and methodology	16	
2	Stat	e of the art	10	
6	21	Definition of slurry flow properties	20	
	$\frac{2.1}{2.2}$	Isothermal slurry and pressure drop	20	
	2.2	2.2.1 Horizontal pipe flows	21	
		2.2.2 90 ° bend flows	25	
		2.2.3 Vertical pipe flow	$\frac{-0}{27}$	
	2.3	Non-isothermal slurry: heat transfer coefficient	$\frac{-1}{28}$	
	2.4	Modeling of fluid-particles interaction	32	
		2.4.1 Euler-Lagrangian approach: particles tracking	34	
		2.4.2 Euler-Euler approach: two-fluids model	37	
	2.5	Dimensionless analysis	40	
		2.5.1 Energy equation	42	
	2.6	Conclusive remarks	46	
3	Exp	erimental methods	40	
2	3.1	Mixtures selection	50	
	1.1.1	3.1.1 Isothermal case	50	
		3.1.2 Non-Isothermal case, without phase change	52	

Contents

	3.2	Experimental facilities	53
		3.2.1 The PREDICT facility	53
		3.2.2 The heated section	55
	3.3	Non-conventional measurement techniques: capacitance sensor	59
		3.3.1 Working principle	60
		3.3.2 Design of the sensor	60
		3.3.3 Numerical calibration of the sensor	64
		3.3.4 Experimental validation of the capacitance sensor	66
	3.4	Flow visualization	70
	0.1	3.4.1 Image post-processing for solid volume fraction measurement	70
		3.4.2 Image post-processing for particles velocity measurement	73
	35	Traditional measurement techniques	76
	5.5	3.5.1 Coriolis flow meter	76
		2.5.2 Program transducors	77
		2.5.2 Temperature measurement	78
	36	5.5.5 Temperature measurement	80
	0.0	2.6.1 Processing drop	80
		2.6.2 Heat transfer coefficient	80
	97	D.0.2 Heat transfer coefficient	00 00
	3.7	Summary	82
4	Nun	nerical modeling	83
<u>.</u>	4 1	Governing equations	84
	$\frac{1.1}{4.2}$	Closure and modeling strategies	85
	1.2	4.2.1 Turbulence modeling	85
		4.2.2 Granular kinetic theory	86
		4.2.2 Oranual kinetic file in exchange	90
		4.2.4 Interphase energy exchange	92
	43	Geometrical domain	94
	$\frac{1.0}{4}$	Boundary conditions	96
	1.1	4.4.1 Inlet and outlet sections	96
		4 4 2 Wall boundaries	97
	4.5	Numerical settings	100
	4.6	Summary	101
	1.0	<u>Summary</u>	101
5	lsot	hermal Slurry: Flow pressure drop	103
	5.1	Horizontal section	104
		5.1.1 Experimental results: pressure drop and flow regimes	104
		5.1.2 Validation of the Euler-Euler solver	110
	5.2	90 ° vertical bend section	115
		5.2.1 Discussion of the experimental results	115
		5.2.2 Numerical simulations with the Euler-Euler model	118
	5.3	Vertical section	122
		5.3.1 Results of the experimental campaign	122
		5.3.2 Numerical study with the Euler-Euler model	125
	5.4	Conclusions on the isothermal flow of slurry in pipes	129

 \mathbf{viii}

Contents

6	Non	-isothermal slurry: flow heat transfer coefficient	131		
	6.1	Preliminary fully liquid flow analysis	132		
		6.1.1 Experimental results	132		
		6.1.2 Assessment of the CFD model in fully liquid conditions	136		
	6.2	Slurry in non-isothermal conditions: experimental results	139		
		6.2.1 Flow regimes characterization	139		
		6.2.2 Temperature profiles modification	143		
		6.2.3 Heat transfer coefficient modification	144		
	6.3	Euler-Euler solver in non-isothermal conditions: challenges and capa-			
		bilities	151		
	6.4	Conclusions on the non-isothermal flow of slurry in pipes	157		
_					
7	Con	clusions and future perspectives	161		
	7.1	Summary and main contributions	162		
	7.2	Future perspectives	165		
_			1.00		
Α	Deb	ugging tests on the PREDICT heated section	169		
	A.1	Analysis of the current supplied to the heated test section	169		
	A.2	On the uniformity of the heat flux provided to the heated section.	170		
Bi	Bibliography				

 $\mathbf{i}\mathbf{x}$