Mathematical Model of Ice Slurry Flow to predict Agglomerations and Phase interaction effects

Shaimaa Hefny Badawi
Technical University Dresden, Bitzer-Chair of Refrigeration, Cryogenics and Compressor Technology, Germany, shaimaa.hefny@tu-dresden.de

Christiane Thomas
Ullrich Hesse

Follow this and additional works at: https://docs.lib.purdue.edu/iracc

Badawi, Shaimaa Hefny; Thomas, Christiane; and Hesse, Ullrich, "Mathematical Model of Ice Slurry Flow to predict Agglomerations and Phase interaction effects" (2021). International Refrigeration and Air Conditioning Conference. Paper 2226.
https://docs.lib.purdue.edu/iracc/2226

This document has been made available through Purdue e-Pubs, a service of the Purdue University Libraries. Please contact epubs@purdue.edu for additional information. Complete proceedings may be acquired in print and on CD-ROM directly from the Ray W. Herrick Laboratories at https://engineering.purdue.edu/Herrick/Events/orderlit.html
Mathematical model of ice slurry flow to predict agglomerations and phase interaction effects
Shaimaa HEFNY*, Christiane THOMAS, Ullrich HESSE

Technical University Dresden,
Faculty of Mechanical Science and Engineering,
Institute of Power Engineering,
Bitzer-Chair of Refrigeration, Cryogenics and Compressor Technology,
01062 Dresden, Germany,
shaimaa.Hefny@tu-dresden.de
christiane.thomas@tu-dresden.de
ullrich.Hesse@tu-dresden.de

* Corresponding Author

ABSTRACT
Ice slurry is an energy-intensive secondary fluid, which may play an important role in various cooling purposes. From the system design perspective, it is of great importance to obtain detailed information of the ice slurry flow. A quantification of the complex two-phase flow characteristic is difficult due to the heterogeneous ice slurry flow. The paper includes the theoretical analysis of the ice slurry behaviour with different ice particle conditions (concentration, size) considering pressure drop and agglomeration. In addition to the mathematical model analyses of all important balance equations and other sub-equations (granular properties, phase interactions), various parameters influencing the behaviour of the ice slurry are considered. The CFD software has been successfully used to simulate the application of phase change material (PCM) in different technical applications, including cooling and air conditioning technologies. Based on the kinetic theory of granular flow, the ice slurry flow is described with and without consideration of melting. The Eulerian model provides granular properties and phase interaction parameters for the liquid-particle flow (ice slurry) to investigate particle collisions, drag, lift and turbulence dispersion. The numerical results were in good agreement with the experimental data from the literature.

Keywords: Ice Slurry, CFD, Simulation, Phase Interactions, Pipeline, Agglomeration

1. INTRODUCTION
Ice slurry has recently been utilized for a variety of technical fields, such as thermal energy storage and high-density energy transport. The key issue of using ice slurry is the reliable, energy-efficient and cost-effective (cheap) production of the ice slurry. Ice slurry as a secondary refrigerant is a very interesting solution thanks to the high cooling capacity given by the latent heat of the phase change. Ice slurry is a so called phase change material (PCM). It is a mixture of fine ice particles/crystals (typically 0.1 to 1 mm in diameter) and a liquid binary solution. The simplicity of freezing water with an environmentally friendly additive (alcohol, salts, etc.) and obtaining very high enthalpy densities makes the application of ice slurries a promising technology for the future (Michael Kauffeld 2005). The fully suspended ice-slurry flow in a horizontal pipe was analyzed (Mellari 2016); it was shown that the ice slurry can be treated as Newtonian fluid at higher average fluid flow velocities, and lower average ice particle concentrations as well. When the ice concentration increases and velocity decreases, the viscosity depends not only on the ice concentration but also on the average velocity and the pipe diameter. The ice slurry then behaves as a non-Newtonian fluid. The pressure drop behavior of ice slurry based on mono-propylene glycol (MPG) water in a circular horizontal pipe was investigated experimentally (Mellari 2016). The non-Newtonian character of ice slurry was confirmed and its rheological parameters were experimentally determined (consistency index and flow index). The ice slurry flows shear-thinning (n<1) or shear-thickening (n>1) and sometimes the moving bed occurs as Newtonian flow (n=1). The results show that the pressure drops increase with increasing ice fraction and that the pressure drops becomes larger at small...
velocities (Mellari 2016). The heat transfer coefficients and pressure drops were investigated experimentally for the ice slurry flowing in the inner pipe with ice mass fraction ranging from 0% to 30% and with flow velocities between 0.3 and 1.9 m·s⁻¹. Their results showed that an increase in the ice fractions causes a change in the flow structure of the ice slurry, which influences the evolution of the pressure drops and the heat transfer coefficients (Bédécarrats, Strub et al. 2009). (Asaoka, Tajima et al. 2016) experimentally investigated inhomogeneity in ice slurry, which can cause problems such as sudden increase in pressure drop and blockages in flow. It was found that the fluctuation of the pressure drop is relatively small at the beginning, but becomes larger after longer periods of time. Moreover, when the temperature difference is large, the ice slurry solidifies on the tube wall and the pressure drop increases with time (Kumano, Mizui et al. 2018). (Onokoko, Poirier et al. 2018) presented a 3D computational fluid dynamics (CFD) model in which the ice slurry is treated as a Newtonian fluid with effective properties depending on the local ice fraction, and experimentally investigated the properties of a propylene glycol ice slurry flow through a long horizontal pipe. (Niezgoda-Zelasko 2006, Niezgoda-Zelasko 2006, Niezgoda-Zelasko and Zalewski 2006)) presented results of various studies in which the ice slurry flow in horizontal tubes was investigated experimentally and numerically. The non-Newtonian character of the ice slurry flow was confirmed; it was also found that with increasing fraction of solid particles, the loss of stability of the laminar flow occurs at higher values of flow velocities. It was shown that in the laminar domain the selected models (Bingham and mixture model) provide a correct description of momentum transfer. In the turbulent region, corresponding to low values of the Reynolds number, the best agreement between experimental and simulation results was found using the multiphase Eulerian model (Niezgoda-Zelasko 2006, Niezgoda-Zelasko 2006, Niezgoda-Zelasko and Zalewski 2006). (Mellari, Boumaza et al. 2012)) presented physical modelling, numerical simulation and experimental investigations of non-Newtonian ice slurry flows consisting of mono-propylene glycol as an additive. (Wang, Zhang et al. 2013, Wang, Wang et al. 2017) presented the fundamental theory and models to describe how ice particles in a heterogeneous ice slurry affect the fluid flow and pressure drop in horizontal pipes based on experiments and validated the numerical approach. In addition, they applied a computational fluid dynamics (CFD) model based on the different rheological behavior to characterize the heterogeneous ice slurry flow. Compared to the experimental data, the numerical model provided an excellent prediction, with relative errors limited to ±15% in almost all cases. Furthermore, they investigated the numerical model of the isothermal flow of the ice slurry in different pipes (Wang, Wang et al. 2013).

2. STATE OF ART

The aim of this section to describe the behaviour of ice slurry in order to find the right models for testing and simulating ice slurry in different heat exchanger structures. The regimes behavior of ice slurry has to be defined in order to choose a suitable multiphase model for the simulation.

2.1 Multiphase regimes:
Multiphase regimes approaches and models must be determine for the analysis and simulation of ice slurry flow inside any structure of channels. Multiphase flow regimes can be divided into four categories: gas-liquid or liquid-liquid flows; gas-solid flows; liquid-solid flows; and three-phase flows (Guide 2018). Ice slurry is classified as liquid-solid (binary solution/ice particles). Ice slurry, on the other hand, can occur with three types of regimes: slurry/ hydro transport, sedimentation and fluidized bed. Furthermore, there is another simple regime classification for ice slurry as shown in Figure (1):
1. Homogeneous: the solid particles are almost uniformly distributed across the cross-section of the pipe.
2. Heterogeneous: there is a concentration gradient in the direction perpendicular to the pipe axis, with more particles transported in the lower part of the pipe cross-section.

![Figure 1: a) Homogeneous flow, b) heterogeneous flow in a pipe](image_url)
2.2 Ice Particle Shape:
In reality, ice particles are asymmetrical. However, for calculations and simulations they are often assumed to be spherical. The particle diameter (DS) was assumed for the individual particles in the simulation. The ice particle diameter of individual particles can be determined with a camera and a transparent experimental setup, but the agglomeration of the particles is very difficult to detect due to the high flow velocity. When agglomerated particles were considered for the simulation, an elliptical agglomeration was assumed with the dimension (LS) as length of the ellipse formed. The agglomeration length represents the longest distance of the agglomeration of particles, whereby the term "agglomeration" applies to coherent particles that are assumed to be about 10 times the size of a single particle. Numerous experiments were carried out at the in ILK Dresden and other research institutions like (Koffler 2019) to determine the ice particle size and agglomeration size/length.

![Figure 2: Ice particle shape in reality and assumptions for simulation](image)

3. MATHEMATICAL MODEL

The flow of ice slurry in a horizontal circular pipe is considered. An inlet condition with uniform velocity is applied, where the inlet velocity is in the direction of the pipe axis. The inlet conditions for ice slurry flow are a varying concentration of the additive solution, mixing with water, and a varying inlet temperature, whereby the spherical ice particles have a uniform size (homogenous slurry). No-slip boundary conditions for the liquid phase and particle slip conditions for the solid phase are used. In the case of an isothermal flow (without melting), a uniform heat rate of zero (adiabatic wall) is applied to the wall. A three-dimensional Euler-Euler granular multiphase turbulence model based on the kinetic theory of granular flow was used by used multiphase model (two phases) for the simulations. In the Euler-Euler approach, ice particles and water-additive solution are treated as continua. One option used in solving this problem is to start with a simpler multiphase mixture model and then choose the Eulerian model. In the Euler-Euler approach, both the solid and liquid phases are treated mathematically as interpenetrative continua involving interphase momentum exchange. Besides, the conservation equations for each phase are applied to obtain a set of Reynolds-averaged Navier-Stokes equations. When working on ice particles, these equations are closed by applying the kinetic theory. It is important to recognize that the exchange of momentum of the particles in the kinetic theory is only due to translation and collision. The model accounts for the effects of interphase forces of drag, lift, turbulence dispersion, and particle-particle and particle-wall collisions by incorporating interphase terms and the turbulence model. The second-order upwind scheme was utilized. The discrete equations were solved with the phase-coupled SIMPLE algorithm in ANSYS Fluent Theory (Guide 2018). A mesh curvature/proximity based refinement is then required in the near-wall regions. The mesh expansion rate is fixed to 1.1. The mesh grid is composed of 2.5 x 10^6 elements and The mesh size is 0.1mm.

3.1 Continuity Equation
For liquid and solid phases, the continuity equation can be expressed as follows:

For liquid phase as the primary phase, the following applies:

$$\frac{\partial}{\partial t}(\alpha_l \rho_l) + \nabla \cdot (\alpha_l \rho_l \mathbf{U}_l) = \dot{m}_{sl}$$  \hspace{1cm} (1)

For solid (ice particle) phase as a secondary phase, it can be noted:

$$\frac{\partial}{\partial t}(\alpha_s \rho_s) + \nabla \cdot (\alpha_s \rho_s \mathbf{U}_s) = -\dot{m}_{sl}$$  \hspace{1cm} (2)
The local volume fraction relation between liquid and solid phases is given by:
\[ \alpha_l + \alpha_s = 1 \]  

### 3.2 Momentum Equations

The momentum balance for each phase is expressed along with the interphase momentum transfer. Momentum equations are established for both the liquid phase and the solid phase:

**Liquid phase**
\[
\frac{\partial}{\partial t} \left( \alpha_l \rho_l \mathbf{U}_l \right) + \nabla \cdot \left( \alpha_l \mathbf{U}_l \mathbf{U}_l \right) = -\alpha_l \nabla P + \nabla \cdot \mathbf{t}_l + \alpha_l \rho_l g + \bar{R}_{l}\]

**Solid phase**
\[
\frac{\partial}{\partial t} \left( \alpha_s \rho_s \mathbf{U}_s \right) + \nabla \cdot \left( \alpha_s \mathbf{U}_s \mathbf{U}_s \right) = -\alpha_s \nabla P + \nabla \cdot \mathbf{t}_s + \alpha_s \rho_s g + \bar{R}_{l}s
\]

### 3.3 Solids Shear Stresses:

It is assumed that the granular properties for ice slurry flow are important because the granular model includes models that account friction and collisions between particles, as shown in Figure (3). The shear viscosity \( \mu_s \) of the solid phase is based on the granular kinetic theory (GIDASPOW 1994).
\[
\mu_s = \mu_{s,cot} + \mu_{s,kin} + \mu_{s,fr}
\]

**Figure 3:** Pictorial explanation of kinetic, collisional and frictional viscosities (Kaushal, Thinglas et al. 2012).

The collision part of the shear viscosity is modelled as follows:
\[
\mu_{s,cot} = \frac{4}{5} \alpha_s \rho_s d_s g_{o,ss} (1 + e_{ss}) \left( \frac{\sigma_s}{\pi} \right)^{0.5} \alpha_s
\]

For the kinetic part of the shear viscosity, there are two expressions as follows:
\[
\mu_{s,kin} = \frac{\alpha_s \rho_s d_s \sqrt{\rho_s}}{6(3-e_{ss})} \left[ 1 + \frac{2}{5} (1 + e_{ss})(3e_{ss} - 1) \alpha_s g_{o,ss} \right]
\]

The secondary volume fraction for solid phase approaches the packing limit; the generation of stress is mainly due to friction between the particles. The shear viscosity of the solid phase contributes to the friction between the particles.
\[
\mu_{s,fr} = \frac{p_{fr} \sin \theta}{2 \sqrt{l_{20}}}
\]
The model of Johnson and Jackson (Jackson 1987) for frictional pressure is defined as:

\[ p_{fr} = Fr^{(\alpha_s - \alpha_{s, min})^n / (\alpha_{s, max} - \alpha_s)^p} \]  

(12)

Here Fr is a function of the volume fraction, which is calculated as follows: \( Fr = 0.1\alpha_s, \) \( \alpha_{s, min} \) is the minimum packing limit, \( \alpha_{s, max} \) is the maximum packing limit (default value 0.63), and the coefficients \( n=2 \) and \( p=5. \)

The bulk viscosity (\( \xi_s \)) accounts for the resistance of the solid particles to compression and expansion (Lun, Savage et al. 1984).

\[ \xi_s = \frac{4}{3} \alpha_s \rho_s d_s g_{o, ss} (1 + e_{ss}) \left(\frac{\rho_s}{\rho}ight)^{0.5} \]  

(13)

\( e_{ss} \) is the coefficient of restitution for particle-particle collisions, that quantifies the elasticity of particle-particle collisions (default value \( e_{ss} =0.9 \)). \( \Theta_s \) is the particle temperature calculated using the kinetic theory of granular flow and is proportional to the kinetic fluctuation energy of the particles (GIDASPOW 1994). \( g_{o, ss} \) is the radial distribution function for solid particles, which can also be seen as the probability of interaction between particles (Satoru Ogawa 1980).

\[ g_{o, ss} = \left[1 - \left(\frac{\alpha_s}{\alpha_{s, max}}\right)^{1/3}\right]^{-1} \]  

(14)

The pressure of the solid phase is composed of a kinetic term and a second term due to particle collisions:

\[ p_s = \alpha_s \rho_s \Theta_s + 2 \rho_s (1 + e_{ss}) \alpha_s^2 g_{o, ss} \Theta_s \]  

(15)

The granular Temperature \( \Theta_s \) for the solids phase is proportional to the kinetic energy of the random motion of the particles .

\[ \Theta_s = \frac{1}{3} \vec{\Theta_s} \cdot \vec{U_s} \]  

(16)

### 3.4 The Phase Interactions:

The phase interactions define important parameters that describe the interaction between the individual phases in Eulerian model. The effect of the interactions was investigated numerically with validation by the experimental results for the solid-liquid flow in previous papers, e.g. (Shaimaa HEFNY 2019). The parameters of the phase interactions include all forces acting on the particles. The analysis of the forces affecting the particles are shown in Figure (4) inside a horizontal tube.

a. The virtual mass force (\( F_{vm} \)) occurs when the secondary solid particle phase is accelerated relative to the primary liquid phase. The coefficient of virtual mass force is set to 0.5 by default;
b. The coefficient of the drag force (\( F_D \)) is chosen according to the Schiller-Nauman model (Schiller 1935);
c. The lift force (\( F_L \)) is the force perpendicular to the direction of flow (Drag force) due to the shear stress of fluid. The coefficient of the lift force is chosen according to the Morage model (Lahey 1993);
d. The buoyancy force (\( F_B \)) is the force acting against the direction of gravity and acting on all objects submerged in a fluid. When an object is immersed in a fluid, the object’s weight pushes down on the fluid (liquid or gas), while an upward buoyancy force pushes up on the object and acts against gravity.
e. The gravity force (\( F_G \)) is the force due to the gravity and in the opposite direction of the buoyance force
f. The external force (\( F_{Ext} \)) is the force due to the pressure gradients of flow.
3.5 Energy Conservation:
To account for heat transfer in ice slurry, the following applies for liquid phase:

\[
\frac{\partial}{\partial t} (\alpha_l \rho_l H_l) + \nabla \cdot (\alpha_l \rho_l \vec{U}_l H_l) = \nabla \cdot (\lambda_{eff} \nabla T_l) + \tau_l \cdot \nabla \vec{U}_l - h_0 (T_l - T_s) + \dot{m}_{sl} (H_s + H_l)
\]  

(17)

for the solid phase:

\[
\frac{\partial}{\partial t} (\alpha_s \rho_s H_s) + \nabla \cdot (\alpha_s \rho_s \vec{U}_s H_s) = \nabla \cdot (\lambda_{eff} \nabla T_s) + \tau_s \cdot \nabla \vec{U}_s - h_0 (T_s - T_l) - \dot{m}_{sl} (H_s + H_l)
\]  

(18)

3.6 Turbulence Model:
The RNG k-\(\varepsilon\)-turbulence model using the Reynolds-normalisation group (Yakhot, V., et al., 1992.) is used for the simulation of all cases to account for the effects of smaller scales of motion. The constant parameters of the turbulence model used in the equations are assumed as:

\[C_\mu = 0.09, \quad C_{1\varepsilon} = 1.44, \quad C_{2\varepsilon} = 1.92, \quad C_{2\varepsilon} = 1.2, \quad \sigma_k = 0.9, \quad \sigma_\varepsilon = 1.3\]

4. DATA REDUCTION

The pressure loss depends on the particle parameters such as size (\(d_s\), or \(L_s\)), structure, thermophysical properties, volume fraction (\(\alpha_s\)), interaction forces (\(\sum F_i\)), and shear stress viscosities (\(\sum \mu_s\)). Other influences are the boundary conditions of the system such as the velocity as well as the structure of the heat exchanger. In the case of a tube flow, these are the tube diameter (\(D_t\)) and the length of the tube (\(L_t\)). When considering a plate heat exchanger, it is the length (\(L_{ch}\) ) , width (\(W_{ch}\)) and height (\(H_{ch}\)) of the channels of plate.

\[\Delta P = f\left(\begin{array}{c}
\text{Particle -- Parameters,} \\
\text{Boundary Conditions,} \\
\text{Heat Exchanger Geometry}
\end{array}\right)\]

\[\Delta P = f(d_s, L_s, \alpha_s, \sum F_i, \sum \mu_s, \nu, (D_t, L_t), \text{or}(L_{ch}, W_{ch}, H_{ch}))\]

5. VALIDATION

The validation was carried out in various cases for different parameters (volume flow rate, particle concentration, particle sizes) with corresponding experimental data from the literature and the Institute of Air Handling and Refrigeration (ILK), in Dresden, Germany. For comparison with the actual flow, flow information about velocity, concentration and pressure drop profiles are calculated. For the experimental investigations, a high speed camera was used to resolve the velocity profile of the ice particles in the horizontal circular pipe. The length of the pipe was 3.5 m and the diameter was 21.7 mm. Volume flows of 1.6, 2, 3 and 4 m\(^3\)/h were investigated with a potassium format water solution, ice particles with a diameter of about 500 μm and ice contents ranging from 0 % to 30 %. The comparison
of the results predicted by the simulation and the experimental results for the pressure drop in the pipe at different ice concentrations is shown in Figure 6. The validation shows the agglomeration prediction of relative pressure drops depending on the ice concentration. The numerical investigations were performed in two different ways: First, the ice particles were assumed to be spherical with a diameter (ds) of 0.3 mm at different volume flows (dotted curves). In a second case, the agglomeration structure was assumed to be elliptical with an ellipse length (Ls) of 3 mm (dashed curves). It was found that the pressure losses for the simulation of the ice particle diameter and the agglomeration length are almost the same for low ice concentrations (0 % - 5 %). For higher ice concentrations (5 % - 30 %), there is good agreement between the numerical investigations for the agglomeration length and the experimental results. The results shown in Figure 6 can be divided into three sections:
a) an almost constant pressure drop at ice concentrations between 0 % and 15 %, whereby the behaviour of a Newtonian flow can be assumed;
b) a local minimum of the pressure drop with a transition from Newtonian flow to non-Newtonian flow;
c) a range from local minimum to local maximum of the pressure drop at high ice concentration.

Only individual fluid parameters such as shear stress rates, interactions and agglomeration can be assumed as the cause for this change of the flow behavior.

![Graph](image)

**Figure 6:** Validation of the pressure drop between experimental and simulation results in a horizontal tube for ice particle diameter ds = 0.3 mm and agglomeration length of the ice particles Ls = 3 mm

Figures (6) and (7) show the distribution of ice particles along the cross section of the pipe at the distance L from the pipe inlet. The results show that the ice fraction distribution in the cross section of tube becomes heterogeneous along the length of the tube. The heterogeneity of ice particles and water solution is visible. It can be seen that ice particles float due to the lower density of the ice particles compared to the water solution. For the ice particle diameter (ds), the difference between the maximum and minimum volume fraction distribution is very small. Accordingly, the ice fraction map in Figures (6) and (7) depicts a larger ice fraction in the upper of the tube and a depletion in the lower half. For the agglomeration length (Ls), the results show a high ice fraction in the middle of pipe cross section. For homogeneous flows, the ice concentration is more uniformly distributed along the radial direction at a given axial position as shown in Figure (7) at ds = 0.3mm. For Heterogeneous flows are observed at low inlet velocities providing a non uniform ice particle distribution. Ice particles are mainly concentrated at the top wall of the pipe as shown in Figure (7) at ds = 0.3mm.
6. DISCUSSION

The next investigations will focus on improving the modelling of flow and heat transport processes when using ice slurry and on optimizing the designs of heat exchangers in general. Investigations on heat exchangers show that plate heat exchangers would be a good choice to enhance the efficiency of a system and to obtain simple and compact heat exchangers. An important point to investigate is the optimization of new structures of plates available for ice slurry flow without agglomeration in the channels, as well as optimization of the distribution at the inlet and outlet of plate heat exchangers with low-pressure drops.

7. CONCLUSIONS

In this paper, summaries of CFD models are presented with guidelines for the use of suitable models in order to obtain good agreement results in the validation of the ice slurry simulation compared to experimental results. The parameters of granular properties (shear stress viscosities including kinetic, collision and friction viscosities) and phase interactions (virtual force, buoyancy, attraction between particles, buoyancy, and gravity) are further factors that influence the ice particles and are needed for comparison with experimental results. The effects of changing these factors are most noticeable at the high ice concentrations and agglomeration size for solid-liquid flows. The numerical results of pressure drops as a function of ice concentrations are in very good agreement with the experimental results for ice agglomeration length in a tube. The volume fraction profiles of the ice particles are compared using the ice particle diameter and the agglomeration length. The agglomerations and blockages can be predicted using the CFD code for different plate heat exchanger structures. Thus, the Euler-Euler CFD model can be used to investigate future technologies to improve the efficiency of refrigerant systems.

NOMENCLATURE

\[ \tilde{U} \]  
the local phase velocity \( (\text{m.s}^{-1}) \)

\[ \alpha \]  
the local phase volume fraction \(-\)

\[ \rho \]  
the phase density \( (\text{kg.m}^{-3}) \)
The mass transfer rate due to melting of ice particles. (kg.s⁻¹)
The Pressure (Pascal)
The shear stress
The gravitational acceleration (m.s⁻²)
The shear viscosity (Pa.s)
The specific heat
Latent heat of ice-particles
The turbulence kinetic energy
The angle of internal friction
The bulk viscosity
The unit tensor
accounts for phase-interactions
The solid ice particle diameter (mm)
The agglomeration length (mm)
The enthalpy
The effective thermal conductivity
The interphase heat transfer coefficient
The temperature (°C)
The turbulent dissipation
The second invariant of the stress tensor
The ice concentration inside tube
The height from pipe center in direction Y (m)
The Diameter of the pipe (m)
Ice volume concentration in direction Y

Subscript
l liquid
s solid

REFERENCES

ANSYS Fluent Theory Guide, 2018

ACKNOWLEDGEMENT

The research is funded by the German Federal Ministry for Economic Affairs and Energy (Bundesministerium für Wirtschaft und Energie - Project 03ET1476B).