STUDY ON ICE SLURRY FLOW CHARACTERISTICS BASED ON GENETIC ALGORITHM

by

Shuai HAO, Wenjie ZHOU**, Jiajun WANG, Yudong XIA, and Shu JIANGZHOU

Institute of Energy Utilization and Automation, Hangzhou Dianzi University, Hangzhou, China

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Ice slurry is a solid-liquid phase fluid consisting of a liquid solution and ice particles. It is widely used in life and engineering because of its excellent cold-carrying capacity. In this paper, a genetic algorithm is used to optimize the ice slurry flow with the minimum pumping power as the objective function. The results show that the genetic algorithm can be effectively applied to the optimization of ice slurry flow characteristics within reasonable parameters. In addition, the transport characteristics of ice slurry are also analyzed. The selection of suitable ice mass fraction values under different working conditions can make the transport characteristics optimal.

Key words: *ice slurry, flow characteristic, ice mass fraction, genetic algorithm*

Introduction

Since the beginning of the 21st century, the rapid development of industry and the unreasonable exploitation of resources have caused major problems such as energy waste and ecological damage [1]. In order to reduce the energy consumption of cooling and heating, many measures, technologies, and products related to energy saving have emerged in recent years. district heating and cooling (DHC) [2] is a system in which hot water, cold water, or steam is centrally produced by one or more energy stations in a group of buildings in a certain area. It is then supplied to end-users through a district network to achieve their cooling or heating requirements. As an emerging energy application management strategy, it is promoted because it can arrange energy use scientifically, rationally, and reduce energy consumption [3]. During the operation of these systems, the cooling medium carrying the cooling capacity is transported to the buildings in the target area for cooling through long transmission pipe-lines. The main feature of ice slurry, a new type of phase change cold storage medium, is that it is a solid-liquid mixture of a carrier fluid (pure water or a solution with freezing point inhibitors such as ethanol and sodium chloride) and ice particles. It has the advantages of high energy density, fast response to load changes, excellent fluidity, and heat transfer [4]. If ice slurry is used as the cooling medium in district cooling systems, the cooling capacity of the system can be improved. The amount of piping consumables, the heat exchange area at the cooling end, and the system operation and management costs can also be reduced. In a district cooling system with ice slurry as the cooling medium, the delivery of ice slurry is one of the critical aspects. Finding a balance between the delivery power and the carrying cooling capacity is a key issue in the design optimization of the ice slurry system.

* Corresponding author, e-mail: wenjiezh@hdu.edu.cn

Most of the previous studies on the optimization of ice slurry systems are guided by a concern for operating costs and economic benefits without considering the impact of energy consumption [5]. For example, Chen *et al.* [6] used the dynamic programming algorithm to optimize the ice storage air conditioning (IAC) system while only considering the life cycle cost and pay-back period. Ashok and Banerjee [7] investigated the optimal cold storage capacity for load management. The results of this case study show that peak demand can be reduced by 38% with the optimal chilled water storage strategy under the time-of-use tariff. Dogan *et al.* [8] analyzed data collected during four years of operation at a major supermarket. It was found that the facility's ice storage system recouped its initial costs in its first three years of operation. The system has been in operation since 2016 without any loss of performance, and it continues to reduce the energy cost of air conditioning by about half each year. Wei *et al.* [9] used the data-based adaptive dynamic programming method to solve the optimal control scheme of the IAC system. Numerical results show that using the data-based optimal control method can reduce the operation costs.

In order to amend the failure of previous studies to address the issues of increased power consumption, the genetic algorithm is proposed to optimize the ice slurry system in this paper. Genetic algorithm was proposed by Holland [10] of the University of Michigan in 1965 showing many advantages of genetic algorithms over traditional optimization algorithms. Two most notable are:

– the ability to deal with complex problems and
– parallelism.

Genetic algorithms can deal with various types of optimization, whether the objective (fitness) function is stationary or non-stationary (change with time), linear or non-linear, continuous or discontinuous, or with random noise [11]. Since genetic algorithms are effective in solving combinatorial optimization problems and non-linear multi-model, multi-objective functional optimization problems, they have gained wide attention from many disciplines.

In practice, understanding the flow characteristics of the ice slurry makes it easy to determine the size of the resistance to flow in the pipe network, and the amount of power required to convey it. Therefore, the equipment model can be selected reasonably without causing a lack of power or waste of resources.

In this paper, using the ice slurry delivery power in the pipe-line as the objective function, a genetic algorithm is used not only to achieve the optimization of the ice slurry system, but also to analyze the effects of flow rate and concentration on its optimization. Finally, the ratio of ice slurry carrying cooling capacity to pumping power is used as an index to evaluate the ice slurry carrying cold characteristics, which can more intuitively compare the economics of ice slurry at different working conditions.

Materials and methods

System description

The experimental set-up [12] is shown in fig. 1. The ice slurry is stirred in the storage tank and transferred to the transport pump which is equipped with pressure transmitters on both sides of the test pump. The concentration of the ice slurry is determined by the density measured by a mass-flow meter, and the flow rate is measured by a volumetric flow meter.

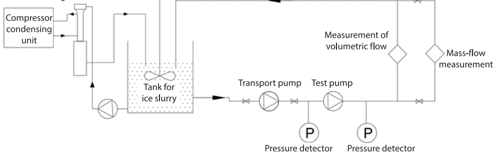

Figure 1. The ice slurry experimental set-up

Ice slurry flow patterns

The flow patterns of ice slurry in tubes can be divided into three categories [13] as shown in fig. 2:

- *Suspension flow*: the suspension flow occurs at a high flow rate with ice particles completely suspended.
- *Moving-bed flow*: the moving-bed flow occurs at a lower flow rate with stratified flow layers, of which the top is a moving-bed layer while the bottom is still a heterogeneous flow layer.
- *Stationary-bed flow*: the stationary-bed flow occurs at a much lower flow rate where the carrier fluid is unable to carry part of the moving-bed layer leading to the forming of a stationary-bed layer at the top of the pipe.

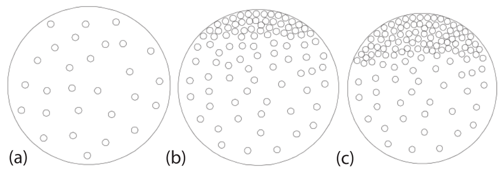

Figure 2. Flow patterns of ice slurry flow [13]; (a) suspension flow, (b) moving bed flow, and (c) stationary bed flow

The critical deposition velocity

Many researchers have found that the pressure drop of the ice slurry increases when it changes from suspended flow to moving bed flow. The critical deposition velocity [14] is determined by the ice slurry velocity when the two flow regimes transform into each other. When the ice slurry flow rate is the critical deposition velocity, the pressure drop value is the minimum. Therefore, in order to reduce the pressure drop and improve efficiency, it is necessary to determine the size of the critical deposition velocity of the ice slurry flow.

Due to the complexity of ice slurry flow in the tube, the critical deposition velocity is often calculated by empirical functions [14]:

$$v_{\min} = 2.8\sqrt{\mathrm{g}D\left(1-\frac{\rho_\mathrm{i}}{\rho_\mathrm{s}}\right)} \tag{1}$$

According to this eq. (1), the critical deposition velocity of 8% NaCl solution at 50 mm diameter is about 0.7225 m/s.

Pressure drop of ice slurry

Fluids are usually classified into Newtonian and non-Newtonian fluids according to their properties. Ice slurry belongs to the category of Newtonian fluids when it is in the initial pure liquid phase state due to the property that phase change occurs between ice and water. The solution starts to crystallize when the temperature is lowered to the solidification temperature [15]. As the temperature continues to decrease, the ice mass fraction gradually increases and reaches a certain level (usually 20%), and the ice slurry changes from a Newtonian fluid to a non-Newtonian fluid.

For a fluid with a known pipe diameter, D, and flow rate, v. The pressure drop per length can be calculated using the Darcy-Weisbach equation:

$$\Delta p = \lambda \frac{L}{D}\frac{\rho v^2}{2} \tag{2}$$

where λ is the can be described by different fluid models. In this paper, a semi-empirical formula for ice slurry flow in heat exchanger proposed by Reghem [16] is adopted:

$$\lambda = f_l + 9330C^{2.07} f_l^{1.963} F_*^{-0.627} \tag{3}$$

The application conditions of this semi-empirical formula are flow rate $v < 4$ m/s, ice slurry mass fraction $10\% < C < 30\%$.

The f_l is the friction factor of the single-phase flow in a tube:

$$f_l = \frac{0.3164}{\text{Re}^{0.25}} \tag{4}$$

The F_* is the Froude number:

$$F_* = \frac{v^2}{gD\left(1 - \frac{\rho_i}{\rho_s}\right)} \tag{5}$$

Fluid-flow can be divided into laminar and turbulent flow with different Reynolds numbers [17]. In order for the ice slurry refrigeration system to ensure the stability and safety of the production process, the flow of ice slurry in the tube must be avoided to appear as a moving bed and a fixed bed. This prevents the phenomenon of ice blockage from causing losses to economic production, so only the turbulent state of ice slurry is considered. The Reynolds number is calculated:

$$\text{Re} = \frac{\rho v D}{\eta_B} \tag{6}$$

where η_B is the fluid viscosity and the effective viscosity of the suspension is usually calculated from the concentration of the carrier fluid (ice slurry). Many different models have been used for the determination of suspension viscosity, and most of them are essentially extensions of Einstein's viscosity equation.

In this paper, the Thomas equation [18] is used to calculate the fluid viscosity:

$$\eta_B = \eta_L \left(1 + 2.5C + 10.05C^2 + 0.00273\text{e}^{16.6C}\right) \tag{7}$$

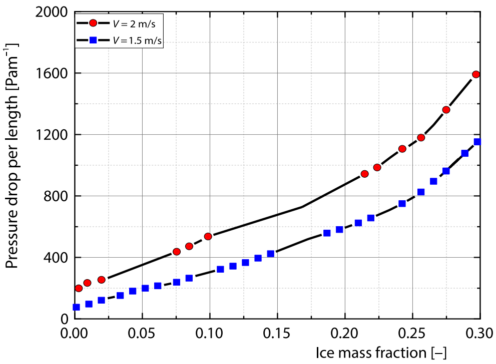

Figure 3. The relationship between pressure drop and ice mass fraction

where η_L is the solution viscosity. To ensure that the ice slurry flowing in the tube is turbulent, the Reynolds number range is selected as $0.64 \cdot 10^4 \sim 4.2 \cdot 10^4$.

Once the pipe diameter and flow rate are determined, we can obtain the relationship between pressure drop and ice mass fraction by eq. (2), as shown in fig. 3.

From fig. 3, it can be obtained that the pressure drop per length increases gradually with the increase of ice mass fraction and flow rate. The pressure drop will have a more obvious effect on the efficiency of the system, which will reduce the cooling capacity and increase the power consumption of the system [19]. Therefore, it is necessary to compensate the pressure or reduce the pressure drop in advance within the design.

In this paper, ice slurry made from NaCl solution is used as the object of study, and a linear weighting method is used to calculate the ice slurry density:

$$\rho_{is} = \frac{1}{\frac{C}{\rho_i} + \frac{1-C}{\rho_s}} \tag{8}$$

which also enables obtaining the relationship between ice slurry density and solution density and ice mass fraction, as shown in fig. 4.

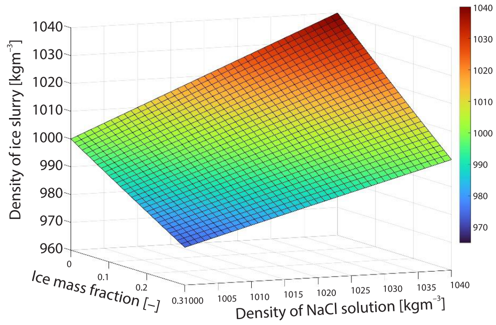

Figure 4. The relationship between ice slurry density and ice mass fraction and solution density

Power consumption

The pressure drop directly affects the power required for the ice slurry to flow through the pipe (*i.e.* pumping power). The pumping power directly reflects the magnitude of the energy consumption, therefore, the pumping power is chosen as the final objective function and optimized. The expression for the pumping power is shown:

$$P = vA\Delta p \tag{9}$$

Optimization method

Genetic algorithm is a part of evolutionary computation, a computational model that simulates the biological evolutionary process of Darwin's genetic selection and natural elimination. It is a method to search for the optimal solution by simulating the natural evolutionary process. The algorithm is simple, general, robust and suitable for parallel processing. An additional advantage over conventional methods such as iterative least squares is that the sampling is global, rather than local. Therefore, it reduces the tendency to become entrapped in local minima and avoids a dependency on an assumed starting model [20].

In summary, genetic algorithms provide a general framework for solving complex system problems. Their overall search strategy and optimal search approach do not rely on gradient information or other auxiliary knowledge in the computation. They only require solving the objective function and the corresponding fitness function that affect the search direction.

The process for implementing the genetic algorithm is:

– Generation of a number of initial populations encoded by a determined length (length related to the accuracy of the problem to be solved) by random means.
– Each individual is evaluated by the fitness function. Those with high fitness values are selected to participate in the genetic manipulation while those with low fitness are eliminated.

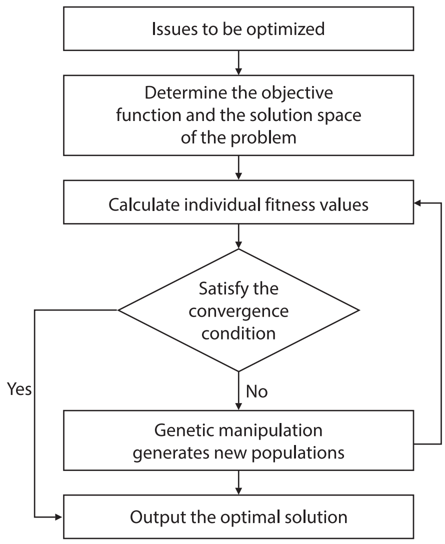

Figure 5. The flow chart of genetic algorithm

– The collection of individuals subjected to genetic manipulation (replication, crossover, mutation) forms a new generation of populations until the stopping criterion is satisfied.
– The best-performing individual among the offspring is used as the result of the execution of the genetic algorithm.

Knowing the flow characteristics of the ice slurry can determine the magnitude of the resistance in the flow and thus the magnitude of the pumping power. Therefore, we select the pumping power, eq. (9), the objective function and use the genetic algorithm for iterative optimization in order to obtain the minimum pumping power under a certain cooling capacity. The flow chart of the algorithm is shown in fig. 5.

Results

The cooling capacity

In practice, the ice slurry flows inside the tube, providing cooling capacity through convective heat transfer. In order to determine the termination criterion of the algorithm, it is necessary to determine the cooling capacity of the ice slurry to deliver, which is mainly expressed as the magnitude of the cooling capacity released when the ice crystal particles undergo phase change. The method for calculating the size of the delivered cooling capacity is shown:

$$Q = vA\left[\rho_{\text{is}}(t_0)h_{\text{is}}(t_0) - \rho_{\text{is}}(t)h_{\text{is}}(t)\right] \tag{10}$$

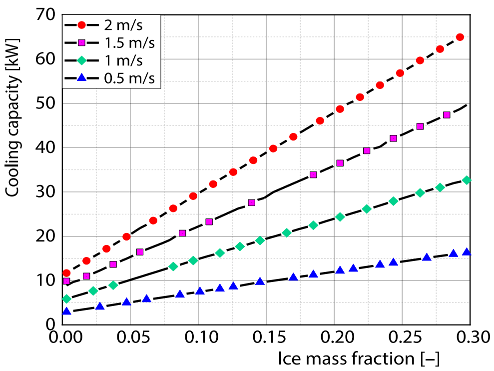

Figure 6. Cooling capacity of ice slurry (*D* = 50 mm)

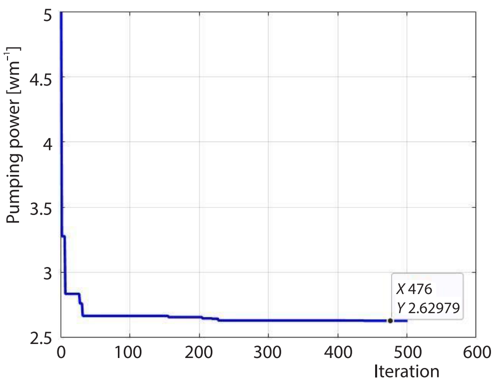

Figure 7. Fitness function against iteration of genetic algorithm

The ice slurry generated from 8% NaCl solution was used as an example to calculate the cooling capacity it carried when flowing in a 50 mm pipe diameter with different mass fraction of ice crystals and flow rate. The calculation results are shown in fig. 6.

From fig. 6, it can be seen that the cooling capacity carried by the ice slurry increases linearly with increasing mass fraction of ice crystals for a certain flow rate.

The convergence test of genetic algorithm

The convergence performance of genetic algorithm based on 50 populations and 500 iterations with a mutation operator of 0.4 and a crossover operator of 0.1 is shown in fig. 7. The fitness function approaches the optimum at around 30 iterations, which indicates that the genetic algorithm using these parameters performs well in terms of convergence.

When the flow rate is kept constant and the algorithm is iterated several times, the relationship between the optimal pumping power, ice mass fraction, and flow rate is obtained as shown in fig. 8.

As can be seen in fig. 8, the trend of increasing pumping power with larger flow rate is obvious. While the pumping power does not change significantly when the ice mass fraction is small, the pumping power increases rapidly after reaching a certain mass fraction.

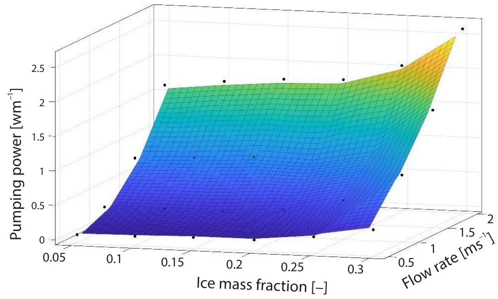

Figure 8. Relationship between pumping power of ice slurry and ice mass fraction and flow rate

Transport characteristic of ice slurry

In general, the higher the ice slurry carrying capacity, the lower the required pumping power and the better the economics and transport characteristics of the slurry. Therefore, the ratio of ice slurry carrying cold quantity to pumping power is used as an index to evaluate the cooling characteristics of ice slurry, which can be more intuitive to compare the economics of ice slurry in different working conditions. The variation of the ratio of ice slurry cooling capacity to pumping power under different working conditions is shown in fig. 9.

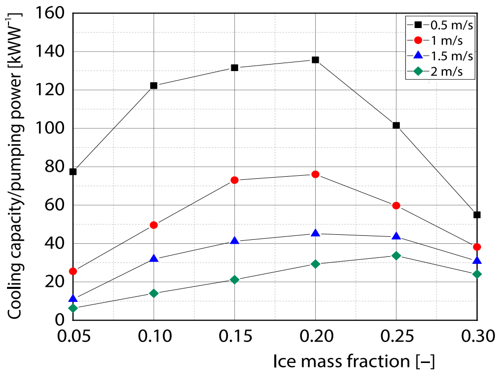

Figure 9. Transport characteristic of ice slurry

As can be seen in fig. 9, the ratio of ice slurry carrying cold to pumping power increases with the ice mass fraction for a certain ice slurry flow rate. When the ice mass fraction reaches a certain value, the ratio starts to decrease rapidly. At the typical flow rate of 1.5 m/s in the pipe-line, the optimal ice mass fraction is 20% with the highest cooling capacity/pumping power of 40 kW. By adopting the genetic algorithm, one can easily find the best ice mass fraction at different flow rate from the energy saving perspective. Furthermore, there exists a value of ice mass fraction when the ice slurry flows in a given size of pipe diameter, which makes the best transport characteristics.

The smaller the flow rate of the ice slurry, the larger the ratio, *i.e.*, the better the transport characteristics. However, too small a flow rate can lead to ice blockage in the pipe-line, so the minimum flow rate needs to be close to the critical deposition velocity so that the pumping power consumption can be reduced while improving the transport characteristics.

Conclusion

In this paper, the flow characteristics of the ice slurry are analyzed. Both the flow rate and the ice mass fraction of the ice slurry directly affect the pressure drop and thus the pumping power. The optimal pumping power to maintain the ice slurry flow is obtained using a genetic algorithm under the condition that no ice blockage occurs. From the genetic algorithm prediction, at the typical flow rate of 1.5 m/s in the pipe-line, the optimal ice mass fraction is 20% with the highest cooling capacity/pumping power of 40 kW. There is always a value of ice mass fraction for ice slurry flowing in the pipe-line that maximizes the ratio of the cooling capacity of the ice slurry to the pumping power. At this value the ice slurry has the optimal transport and economic characteristics under that flow condition.

Nomenclature

A – cross-sectional area of the pipe, [m^2]
C – ice mass friction, [–]
D – pipe diameter, [m]
F_* – Froude number, [–]
f_l – friction factor of the single-phase, [–]
g – acceleration of gravity, [ms^{-2}]
h – enthalpy, [$kJkg^{-1}$]
v – flow rate, [ms^{-1}]
v_{min} – critical deposition velocity, [ms^{-1}]
L – pipe length, [m]
P – pumping power, [Wm^{-1}]
Δp – pressure drop per length, [Pa]
Q – cooling capacity, [kW]
Re – Reynolds number, [–]
t – time, [s]

Greek symbols

λ – friction factor, [–]
ρ – density, [kgm^{-3}]
η_B – effective viscosity, [–]
η_L – solution viscosity, [–]

Superscripts

i – ice crystals
s – solution
is – ice slurry

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