Numerical simulation of heat transfer between low pressure pipeline of pre-mixed abrasive water jet system and low temperature environment

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Abstract. The physical model of low pressure pipeline of pre-mixed abrasive water jet system is established. Based on the software of FLUENT, the numerical simulation of heat transfer between low pressure pipeline of pre-mixed abrasive water jet system and low temperature environment was carried out through solving the continuity equation, momentum equation and energy equation. And the method of determining the maximum length of low pressure pipeline of pre-mixed abrasive water jet system suitable for low temperature environment was confirmed. The simulation results show that: (1) the water temperature decreases along the axial direction with the increase of axial distance at different radial distances, and their descent rates are identical; (2) At different axial distances, the temperature of the material, namely water or pipeline changes along the radial direction the same; for an axial distance, when the radial distance is less than 8mm, the water temperature decreases extremely slow or remains unchanged along the radial direction on the major front of this section; and it decreases by small degrees when the radial distance is close to the wall; and the temperature of pipeline decreases rapidly along the radial direction; (3) The axial temperature drop velocity of water flow in low pressure pipeline are the same at different lengths of low pressure pipeline. It decreases with the increase of ambient temperature and the flux of water flow in low pressure pipeline; and it is almost identical when the entrance temperatures of water flow change little. (4) when the flux of water flow is 12L/min, the entrance temperature is 278.15K, the ambient temperature is 263.15K, 253.15K, 243.15K, 232.15K respectively, the maximum length of low pressure pipeline of pre-mixed abrasive water jet system suitable for low temperature environment is more than 500m, 368.5m, 252m, 187m respectively. This can provide a reference for engineering design of pre-mixed abrasive water jet system suitable for low temperature environment.

Introduction

The abrasive water jet is a kind of water jet which abrasive particle is mixed into. According to the mixing method of abrasive particle and water, abrasive water jet is divided into two classes, namely pre-mixed abrasive water jet and post-mixed abrasive water jet. The pre-mixed abrasive water jet is a kind of high speed liquid-solid two-phase jet that abrasive particle is added into high pressure water pipeline system through a certain technical means in order to make abrasive particle and water be mixed more fully before the jet is ejected out from a nozzle. Because there are a lot of advantages for pre-mixed abrasive water jet, including low working pressure, good effect, easy to be made into portable equipment and suitable for flammable and explosive environment so on, thus pre-mixed abrasive water jet is widely used to cut glass, ceramics, rock, metal, concrete, composite material, brittle material, ductile material etc as a new cold cutting technology. And its application environment also includes inflammable and explosive environment with a presence of high concentration methane or explosive ammunition, under the water, and all kinds of ordinary environment which has no explosion-proof requirements. However, all aforementioned environment are under normal temperature condition. There are few reports about the application of pre-mixed abrasive water jet cutting technology in low temperature environment. On the other hand, the adaptability of pre-mixed abrasive water jet cutting technology in low temperature environment is questionable because water

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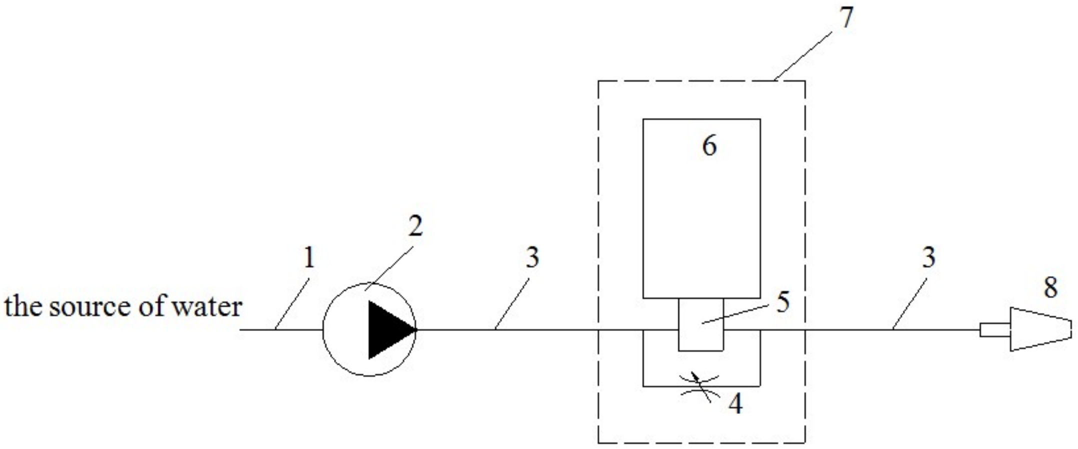
freezes when the temperature falls below 273.15K. Based on the software of FLUENT, the numerical simulation of heat transfer between low pressure pipeline of pre-mixed abrasive water jet system and low temperature environment is carried out in order to make a study of change law of water temperature in low pressure pipeline.

pre-mixed abrasive water jet system and dimensional structure of low pressure pipeline

The structure of pre-mixed abrasive water jet system is shown in Figure 1. It is mainly composed of



1- low pressure pipeline; 2- high pressure pump; 3- high pressure pipeline; 4- throttling valve; 5- mixing chamber; 6- abrasive tank; 7- pre-mixed abrasive adding system; 8- nozzle
Fig. 1 The structure of typical pre-mixed abrasive water jet system

low pressure pipeline, high pressure pump, high pressure pipeline, pre-mixed abrasive adding system and nozzle. Its working principle is: water flowing out of the source of water enters the high pressure pump through low pressure pipeline, and then the pressure of water is enhanced after high pressure pump; abrasive particles is added into high pressure water flow by pre-mixed abrasive adding system. Then the abrasive is mixed with water in high pressure pipeline continuously, resulting that the abrasive is dispersed in water more uniformly and the velocity of abrasive particle increases because of the momentum transfer between abrasive particles and water. Finally, the mixture of abrasive particle and water that the abrasive is mixed with water fully enters pre-mixed abrasive water jet nozzle and the mixture was ejected from the nozzle exit, forming pre-mixed abrasive water jet. Then the materials can be cut when pre-mixed abrasive water jet lashes against the object. Because there is usually no running water interface outside the house in the cold area, such as the Northeast China, and another common source of water, namely the fire-fighting pipe is completely vented before winter to prevent the pipeline from bursting under the condition of low temperature due to freezing of water within the pipe, running water interface inside the house is taken as the source of water of pre-mixed abrasive water jet cutting system in low temperature environment. Compared to the low pressure pipeline, the friction loss is bigger at the same pipeline length and other conditions for high pressure pipeline because the diameter of high pressure pipeline is smaller than that of low pressure pipeline. Meanwhile, it increases running risk of pre-mixed abrasive water jet system if the length of high pressure pipeline is long. Therefore, the length of high pressure pipeline should not be too long in order to reduce the friction loss, namely energy consumption and running risk of pre-mixed abrasive water jet system. And adopting a low pressure pipeline as long as possible is considered in this paper in order to achieve the maximum reachable distance for pre-mixed abrasive water jet system in low temperature environment. By calculating the heat transfer between low pressure pipeline of pre-mixed abrasive water jet system and low temperature environment, the maximum reachable distance of pre-mixed abrasive water jet system in low temperature environment is investigated. In order to calculate the above heat transfer process, physical model of low pressure pipeline has to be established. And in order to ensure that low pressure pipeline can work normally at low temperature up to 232.15K, the low-temperature-resistant material of PEFE is considered to be used to produce low pressure pipeline. Take the flux of pre-mixed abrasive water jet system and pressure requirement of low pressure pipeline into account, the inner diameter of low pressure pipeline is designed as 16mm, and its wall thickness is designed as 1.5mm.

mathematical model

Numerical simulation of the unsteady heat transfer between low pressure pipeline of pre-mixed abrasive water jet system and low temperature environment is carried out through solving continuity equation, momentum equation and energy equation. And the Realizable $k-\varepsilon$ turbulence model is used.

continuity equation

Without considering the influence of the change of water temperature in low pressure pipeline on the density of water, the density of water is constant. The water flow in low pressure pipeline is an incompressible flow and its continuity equation is:

$$\frac{\partial u_x}{\partial x}+\frac{\partial u_y}{\partial y}+\frac{\partial u_z}{\partial z}=0 \tag{1}$$

momentum equation

Without considering the influence of the change of water temperature in low pressure pipeline on the viscosity of water, the viscosity of water is constant. The momentum equation of constant viscous flow is:

$$\rho\frac{d\vec{u}}{dt}=\rho\vec{f}-gradp+\frac{\mu}{3}grad\left(\nabla\cdot\vec{u}\right)+\mu\nabla^2\vec{u} \tag{2}$$

Where $\nabla=\frac{\partial}{\partial x}\vec{i}+\frac{\partial}{\partial y}\vec{j}+\frac{\partial}{\partial k}\vec{k}$; $\vec{f}=f_x\vec{i}+f_y\vec{j}+f_z\vec{k}$; f_x , f_y , f_z stands for the unit mass force (m/s^2) in the direction of x , y , z respectively. Because only the influence of gravity is taken into account in numerical simulation, so $f_x=f_y$=0, f_y f_z=-g . The density of water ρ is 998.2kg/m3and the viscosity of water μ is 1.004×10^{-3}N·s/m^2.

energy equation

The general form of energy equation can be represented as the following equation:

$$\frac{\partial(\rho h)}{\partial t}+\frac{\partial(\rho u_x h)}{\partial t}+\frac{\partial(\rho u_y h)}{\partial t}+\frac{\partial(\rho u_z h)}{\partial t}=-p\mathrm{div}u+\phi+\mathrm{div}(kgradT)+S_\mathrm{h} \tag{3}$$

Where $h=U+pV$; because the simulation object in this paper ,namely water and pipeline are liquid and solid respectively, so there is: $h=c_pT$ .The $p\mathrm{div}u$ is ignored because it is usually very small. ϕ stands for dissipation function of energy that thermal energy is transformed from mechanical energy because of the viscidity; k stands for heat transfer coefficient. S_h stands for thermal energy per unit volume generated by a heat source or radiation, other physical or chemical cause; and $S_\mathrm{h}=\rho q$=0 in this paper because there are no heat source in simulation model and radiation isn't taken into account. Therefore, the energy equation applied in this paper can be simplified to the following equation:

$$\frac{\partial T}{\partial t}+\mathrm{div}(uT)=\mathrm{div}(\frac{k}{\rho c_p}gradT)+\frac{\phi}{\rho c_p} \tag{4}$$

numerical simulation

mesh generation

Considering the axial symmetry of low pressure pipeline, in order to save the time of numerical calculation, the half of low pressure pipeline which achieved by symmetric model modeling, namely splitting low pressure pipeline with the plane that passes the axis of low pressure pipeline, is taken as computational model. Mesh generation of the computational model is carried out by making use of the Meshing application in ANSYS Workbench. Fig.2 is the local enlarged drawing of mesh diagram of a three-dimensional low pressure pipeline. The Sweep method is utilized in mesh generation after the contour line of computational model including 1ine 1, 2, 3, 4, 5, 6, 7 and arc 8, 9 are meshing by Sizing method. And the plane that contains arc 8, 9 is the source surface of Sweep method.

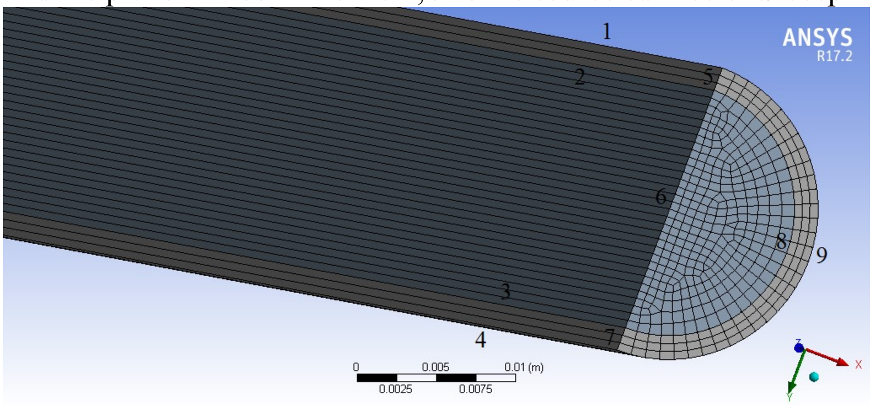


Fig. 2 mesh diagram of a low pressure pipeline

calculation strategy

Taking account of the influence of viscous heating, a double-precision separation solver is adopted in numerical calculations. And the method of near-wall treatment is standard wall functions. As far as the pressure and velocity coupling scheme is concerned, PISO algorithm which has a high convergence speed in transient problem is utilized. Because the heat transfer process between low pressure pipeline of pre-mixed abrasive water jet system and low temperature environment is a coupling process of fluid flow and heat transfer, all hydraulic and thermal boundary conditions should be set up accurately before calculation. The boundary conditions of the flow entrance and flow exit are velocity-inlet and pressure-outlet respectively. And the velocity of the flow entrance is determined according to the mathematical formula: $V = Q/A$; Q and A stand for the flux of water flow in the pipeline and the hollow area of cross-section of low pressure pipeline. The pressure of pressure outlet is set to 0.1MPa referring to the requirement of the flow pressure at the entrance of high pressure pump of a type of pre-mixed abrasive water jet cutting device, namely 0.1~0.3MPa. And both specification method of turbulence in velocity-inlet and pressure-outlet are the method of intensity and hydraulic diameter. Their turbulent intensity are set to 5%. And their hydraulic diameters are equal to the wet perimeter of low pressure pipeline, namely 0.016m. As far as thermal boundary condition is concerned, both cross-section of the entrance and exit of pipeline itself are adiabatic boundary condition; the thermal boundary condition of the inner wall of the pipeline adjacent to water flow is coupled thermal boundary condition. The thermal boundary condition of flow entrance is isothermal boundary condition, and its specific value is the entrance temperature of water flow. For flow exit, backflow total temperature has to be set and its specific value is equal to the entrance temperature of water flow. The thermal boundary condition of the outer wall of the pipeline adjacent to low temperature environment is the convection thermal boundary condition. And its free stream temperature is ambient temperature. In this paper, the heat transfer mode between the outer wall of pipeline and low temperature environment is considered to be natural convection. Because the natural convection heat transfer coefficient between solid wall and air is usually small, about 5~25 W/(m^2·K) and is obtained by a complex iterative computation[11], so the value of natural convection heat transfer coefficient at different ambient temperatures is all set to 9W/(m^2·K) in order to simplify the process of numerical simulation.

analysis on simulation result

change rule of the water temperature in low pressure pipeline

When the length of low pressure pipeline L=200m, entrance water flow Q=12L/min, the entrance temperature of water flow t_1=278.15K, the ambient temperature out of the outer wall of low pressure pipeline t_2=243.15K, the numerical simulation of transient heat transfer process between low pressure pipeline and low temperature environment is carried out. The simulation results show that when the simulation time is above 30min, the results become stable. And the same rules exist in the transient heat transfer process of other conditions. Therefore, the analysis of simulation results of transient heat transfer process between low pressure pipeline and low temperature environment under different conditions are all based on the simulation results of 30min. Fig. 3 is the axial change curve of the water temperature at different radial distances of a longitudinal section which passes the axis of low pressure pipeline when L=200m, Q=12L/min, t_2=243.15K, t_1=278.15K. From the figure, it can be seen that the water temperature at different radial distances decreases with the increase of axial distance in the axial direction and their descent rates along with the axial distance are almost identical. The decline range from flow entrance to flow exit are 3.961K, 3.962K, 3.963K, 3.966K, 3.942K when the radial distance are 0, 2mm, 4mm, 6mm and 8mm respectively. They are very approximate. This is because thermal energy is transferred from water flow in low pressure pipeline to low temperature environment through the wall of pipeline constantly with the increase of axial distance, resulting that the water temperature decreases with the increase of axial distance. On the other hand, the heat transfer process is mainly affected by the thermal conductivity of water and pipeline, natural convection heat transfer coefficient between solid wall and air. And they are constant, so the descent rates of water temperature along with the axial distance are almost identical.

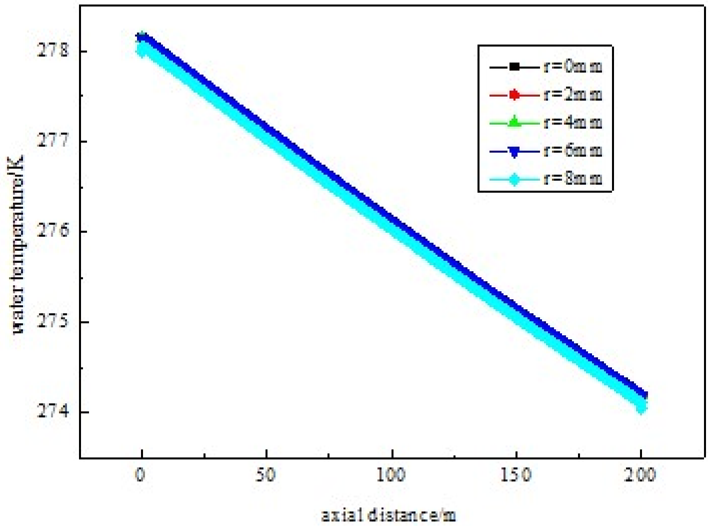


Fig.3 axial change curve of the water temperature at different radial distances

Fig. 4 is the radial change curve of the material temperature at different axial distances of a longitudinal section which passes the axis of low pressure pipeline when L=200m, Q=12L/min, t_2=243.15K, t_1=278.15K. From the figure, it can be seen that the change rules of material temperature along with the increase of radial distance at different axial distances are the same, except that the starting temperature and final temperature are different. For an axial distance, when the radial distance is less than 8mm, the water temperature remained almost unchanged in the most of front of this section; only when the radial distance is close to the wall, the water temperature decreases slightly. And when radial distance is from 8mm to 9.5mm, the material temperature of pipeline decreases rapidly with the increase of radial distance. The reasons are the following: firstly, the water temperature decreases with the increase of axial distance according to the previous analysis; the factors affecting the change of the material temperature along with radial direction at different axial distance are the same, including the thermal conductivity of water and pipeline, and natural convection heat transfer coefficient between solid wall and air; secondly, the main mode of heat transfer in water flow is heat conduction and the thermal conductivity of water is small, namely 0.6w/(m.k); besides, the water temperature has an increase trend because of turbulent mixing of water flow, or rather frictional heat due to the viscosity of water. Therefore, the water temperature decreases slightly in the radial direction. On the other hand, although the thermal conductivity of pipeline is small, namely 0.25W/(m.K), the material temperature of pipeline decreases rapidly because there is a large temperature difference between inner wall and outer wall of pipeline affecting the radial heat conduction inside pipeline. Based on the above analysis, as far as water flow in low pressure pipeline is concerned, the water temperature decreases with the increase of radial distance and the minimum temperature in the radial direction exists on the position of the inner wall of pipeline. In order to prevent water flow in low pressure pipeline from freezing and make sure of the reliability of pre-mixed abrasive water jet system in low temperature environment, the water temperature on the position of the inner wall of pipeline must be above 273.15K. In order to reflect the icing risk of water flow in low pressure pipeline more directly, the water temperature on the position of the inner wall of pipeline is taken as the object of the study in the following analysis.

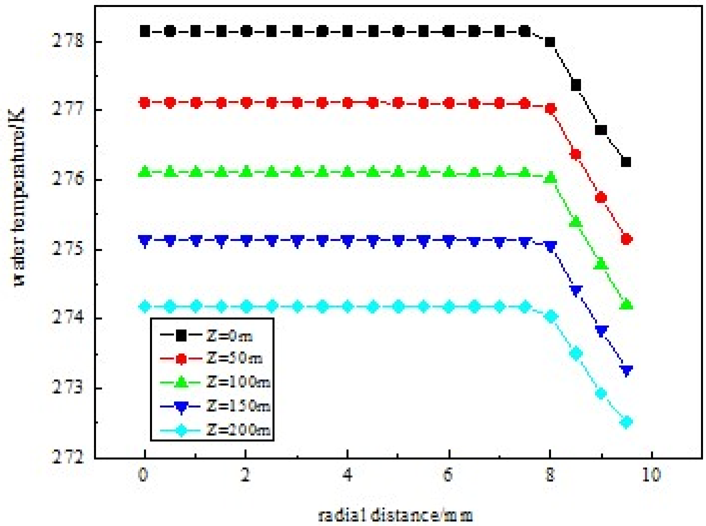


Fig. 4 radial change curve of the material temperature at different axial distances

Influence of entrance temperature of water flow on axial temperature drop

Figure 5 is the axial temperature drop curve of the inner wall of pipeline at different entrance temperature of water flow, namely 276.15K, 278.15K, 280.15K, 282.15K respectively, when L=200m, Q=12L/min, t_2=243.15K.

From the figure, it can be seen that axial descent rates of water temperature are almost identical at different entrance temperature of water flow. The reason for this is that the heat transfer coefficients between water flow and low temperature environment are very approximate because the temperature difference between water flow and low temperature environment is very close at different entrance temperature of water flow and other factors are the same. In fact , it increases slightly because of incremental slightly temperature difference between entrance temperature and low temperature environment. And the decrement of water temperature from the entrance to the exit of low pressure pipeline increases slowly and they are 3.716K, 3.942K, 4.17K, 4.397K respectively when t_1=276.15K, 278.15K, 280.15K, 282.15K. This is mainly because the temperature difference between entrance temperature and low temperature environment increases with the increase of the entrance temperature. And the heat flux, namely the heat loss of water flow increases according to the Newton cooling formula $q = h\Delta t$, at the same length of pipeline and incremental slightly heat transfer coefficients between water flow and low temperature environment.

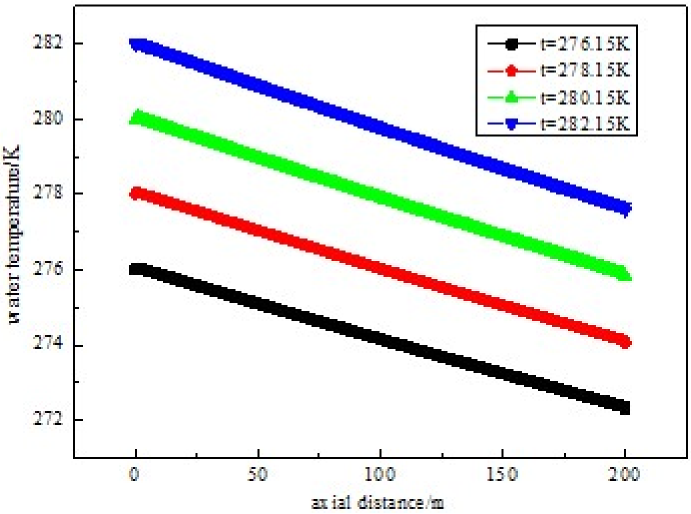


Fig. 5 axial temperature drop curve at different entrance temperature of water flow

Influence of ambient temperature on axial temperature drop

Fig. 6 is the axial temperature drop curve of the inner wall of pipeline at different ambient temperature, namely 263.15K, 253.15K, 243.15K, 232.15K respectively, when L=200m, Q=12L/min, t_1=278.15K.

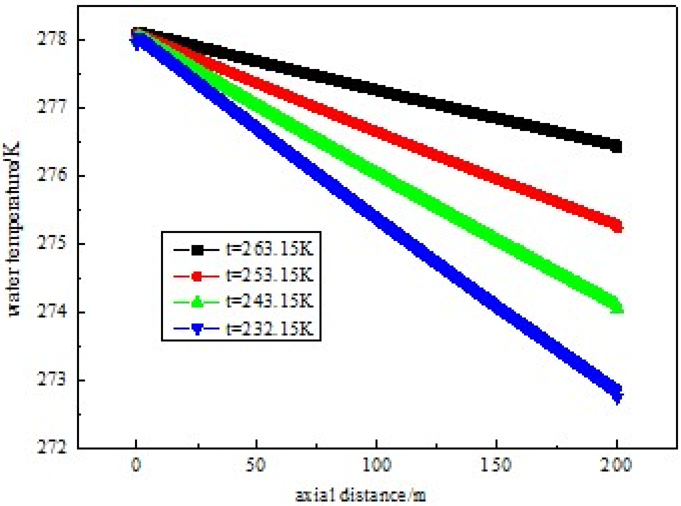


Fig. 6 axial temperature drop curve at different ambient temperature

It can be seen that axial descent rates of water temperature increases with the decrease of ambient temperature. And the decrement of water temperature from the entrance to the exit of low pressure pipeline increases and they are 1.669K, 2.806K, 3.942K, 5.193K respectively when t_2=263.15K, 253.15K, 243.15K, 232.15K. The reasons for this are the same as the reasons described in 3.3.2. That is mainly because the temperature difference between entrance temperature and low temperature environment increases with the decrease of ambient temperature. And at the same length of pipeline, the heat flux, namely the heat loss of water flow increases according to the Newton cooling formula $q = h\Delta t$, because of the increase of temperature difference between entrance temperature and low temperature environment and heat transfer coefficient between water flow and low temperature environment. Meanwhile, because the solidification and melting of water is not considered in the calculation process, according to the simulation result, the water temperature reaches a low temperature 272.749K at the exit of low pressure pipeline indicating that the water may have been frozen when the ambient temperature is 232.15K. Then in turn, the maximum length of low pressure pipeline Lmax that ensure that the water in low pressure pipeline does not freeze and the pre-mixed abrasive water jet system works normally is less than 200m. And simulation results show that when the axial distance Z that stands for the distance from the entrance of low pressure pipeline to the studied position which the water temperature is 273.15K is187m,. It is indicated that Lmax is 187m when the ambient temperature is 232.15K.

Influence of the flux of water flow on axial temperature drop

Fig. 7 is the axial temperature drop curve of the inner wall of pipeline at different fluxes of water flow, namely 10.5L/min, 12L/min, 13.5L/min, 15 L/min respectively, when L=200m, t_1=278.15K, t_2=243.15K.

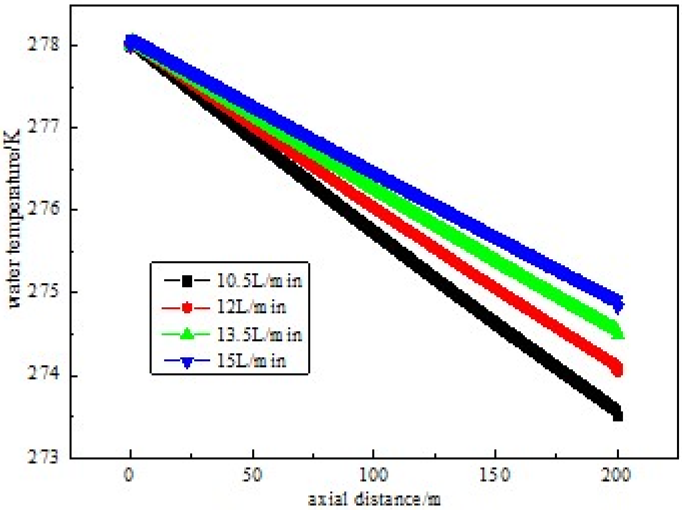


Fig. 7 axial temperature drop curve at different fluxes of water flow

It can be seen that axial descent rates of water temperature decreases with the increase of the flux of water flow. And the decrement of water temperature from the entrance to the exit of low pressure pipeline decreases and they are 4.478K, 3.942K, 3.517K, 3.170K respectively when Q=10.5L/min, 12L/min, 13.5L/min, 15L/min. This is because the velocity of water flow increases with the increase of the flux of water flow. Then the time of heat transfer between water flow and low temperature environment and the heat loss of water flow decreases at the same length of low pressure pipeline and other conditions.

Influence of the length of low pressure pipeline on axial temperature drop

Fig. 8 is the axial temperature drop curve of the inner wall of pipeline at different length of low pressure pipeline, namely 100m, 200m, 300m respectively, when Q=12L/min, t_1=278.15K, t_2 =243.15K.

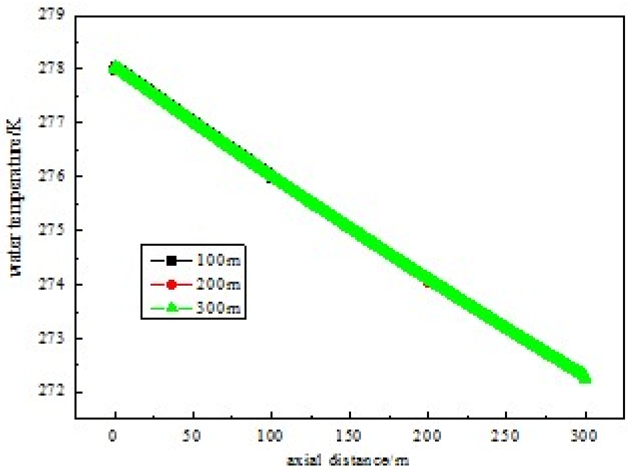


Fig. 8 axial temperature drop curve at different lengths of low pressure pipeline

From the figure, it can be seen that axial descent rates of water temperature are the same at different lengths of low pressure pipeline. And the decrement of water temperature from the entrance to the exit of low pressure pipeline increases and they are 2.028K, 3.942K, 5.744K respectively when L=100m, 200m, 300m. This is because entrance temperature of water flow entrance, ambient temperature, the flux of water flow and the natural convection heat transfer coefficient between the outer wall of pipeline and low temperature environment are all the same. Therefore, the heat flux are the same at different lengths of low pressure pipeline according to the Newton cooling formula $q = h\Delta t$. And the time of heat transfer between low pressure pipeline and low temperature environment and the heat loss of water flow increases with the increase of the length of low pressure pipeline. On the other hand, when the axial distance Z is 252m, the water temperature is 273.16K, approaching the freezing point of water. It is indicated that Lmax is 252m when the entrance water temperature, ambient temperature and the flux of water flow is 278.15K, 243.15K and 12L/min. After calculation, Lmax is 368.5m when Q=12L/min, t_1=278.15K, t_2=253.15K. The maximum length of computational model of low pressure pipeline is 500m due to the limitation of 3D modeling dimension of many modeling software, such as Solidworks, Autocad and so on. When L=500m, Q=12L/min, t_1=278.15K, t_2=263.15K, the water temperature is 274.26K at the exit of low pressure pipeline, namely the axial distance Z=500m. In other words, Lmax is more than 500m on this condition.

Conclusions

(1) At different radial distances, water temperature decreases along the axial direction with the increase of axial distance, and their descent speed are almost identical. Meanwhile, for the same low pressure pipeline and other conditions, the decrement of water temperature from the entrance to the exit of low pressure pipeline are very approximate.

(2) At different axial distances, the temperature of the substance, namely water or pipeline changes along the radial direction the same. For an axial distance, when the radial distance is less than 8mm, water temperature decreases extremely slow or remains unchanged along the radial direction on the major front of this section; And it decreases by small degrees when the radial distance is close to the wall of low pressure pipeline; and the temperature of pipeline decreases rapidly along the radial direction.

(3) The axial temperature drop velocity of water flow in low pressure pipeline are the same at different lengths of low pressure pipeline. It decreases with the increase of ambient temperature and the flux of water flow in low pressure pipeline; and it is almost identical when the entrance temperatures of water flow change little.

(4) The method of obtaining the maximum length of low pressure pipeline of pre-mixed abrasive water jet system suitable for low temperature environment by calculating the heat transfer process between water flow in low pressure pipeline and low temperature environment are confirmed. It can provide a reference for engineering design of pre-mixed abrasive water jet system suitable for low temperature environment. After numerical simulation, the maximum length of low pressure pipeline of pre-mixed abrasive water jet system is more than 500m,368.5m, 252m, 187m respectively when the ambient temperature is 263.15K, 253.15K, 243.15K, 232.15K and the flux of water flow, the entrance temperature of water flow are 12L/min and 278.15K respectively.

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