# Numerical Simulation of Fuel Solidification Process in Fuel Truck Tanks under Polar Environment

**Yuchun Tang*, Baoji Ma**
*School of Defence Science and Technology, Xi'an Technological University, Xi'an, Shaanxi, China*
**Corresponding Author.*

**Abstract: In order to investigate the solidification process of fuel oil in fuel truck tanks under the polar environment, this study is based on the theory of heat transfer, and a two-dimensional model of fuel truck tanks is established to simulate the fuel oil solidification process by using the software FLUENT. Considering the viscosity and temperature change characteristics of the fuel, the change characteristics of the fuel temperature field, velocity field and solidification phase transition during the solidification process are analyzed. The numerical results show that: in the polar environment, the fuel tank storage time of 2.75h fuel tank fuel temperature is lower than its condensation point -44℃, at this time the fuel state can not meet the requirements of the vehicle use, to 374.75h tank fuel solidification, solidification process by the tank wall surrounded by the encircling circle type with the time of the irregular contraction to the inside; Be-fore the fuel temperature is lower than -44℃, the natural convection heat transfer plays a dominant role, and the fuel temperature field distribution changes with the velocity field, after which the natural convection is significantly weakened, and at this time, the fuel temperature is mainly affected by heat conduction, but the fuel temperature drop rate is significantly lower than before. The results of the study can provide some theoretical guidance for the design of fuel tank insulation and heating program for fuel trucks applicable to the polar environment.**

**Keywords: Polar Environment; Fuel Oil; Temperature Field; Velocity Field; Solidification Phase Transition**

## 1. Introduction

In the polar environment, the temperature is extremely low and the energy demand is high. Fuel oil is the main source of providing energy in polar scientific research, which is used for power generation, heating, lighting and transportation, etc. If the fuel supply is insufficient or interrupted, it will pose a threat to the work of polar scientific research and the safety of the personnel. [1,2]-50# diesel fuel is called the exclusive product of the extreme cold region, it is a diesel fuel with excellent performance, compared with conventional diesel fuel, it has a low freezing point, good fluidity, low viscosity, good environmental performance, is a multi-purpose fuel [3]. Fuel truck fuel transportation and storage for the tank loading, but in the polar environment will lead to a large amount of heat loss of fuel tanks lead to phase change of the fuel tank solidification, when the fuel tank solidification is serious not only will cause fuel loss will also happen to condense the tanks and other accidents [4], the polar scientific research on the impact of energy security work. Therefore, in order to re-duce fuel loss and ensure the safe operation of fuel truck tanks, it is necessary to explore the rule of change of fuel temperature in the tank, for the subsequent design of the tank fuel heating program to provide reference. For the study of fuel oil temperature drop and flow characteristics in storage tanks, previous scholars mainly focused on large oil storage tanks and pipelines, using numerical simulation and experimental methods to do a lot of work, and achieved some results. Liang Wenkai [5] and others used ANSYS/Fluent to study the crude oil temperature at different locations in the center section of the storage tank, and found that in the early stage of cooling the crude oil temperature drop near the tank wall gradient is larger. Li Huipeng [6] and others studied the viscosity and rheological properties of diesel oil at low temperature; Yan Yaning [7] and others studied the change of condensation point and cold filtration point of diesel oil before and after the wax precipitation at low temperature by processing, in the low-temperature environment, diesel oil is more likely to coagulate into solid wax lumps, which leads to the loss of fluidity of the oil. Hu Wenpeng [8] studied the heat transfer and mobility of the cooling process of the cargo oil in the tank of a wreck, obtained the temperature and velocity field characteristics of the crude oil inside the tank and analyzed the reasons accordingly. Oliveski [9] and others established a simplified model of a small-volume storage tank, analyzed the temperature drop and the flow law of the crude oil inside the tank, and analyzed the numerical results with the experimental values, and came up with the phenomenon of temperature stratification of the crude oil during the temperature drop process. Yu [10] used the enthalpy-porosity model to analyze the heat transfer process of wax-containing crude oil, and the liquid phase rate and latent heat in the phase transition interval were considered to be uniformly dis-tributed. There are fewer studies on the temperature drop and rheological properties of special cold environments and low condensate diesel oils.

Due to the complexity and variability of the polar environment, the temperature is extremely low, through the experimental simulation of the polar environment to explore the solidification process of fuel tank fuel trucks exist a lot of difficulties, multi-factor integrated climate environment simulation to achieve the difficulty and high cost, and numerical simulation has a time-consuming, invested in the capital cost and the number of staff is small, is not subject to the physical model and the working environment limitations, and many other advantages [11], so this paper for a certain type of off-road Therefore, this paper focuses on the actual engineering project of a certain type of off-road fuel tanker, and utilizes numerical simulation to carry out exploratory research in the first stage. The commercial software ANSYS/FLUENT is used to numerically simulate the fuel solidification process in the fuel tank of a fuel truck under the polar environment, focusing on analyzing the fuel temperature and the distribution of the solidified oil layer near the tank wall and the tank bottom, as well as its influencing factors. The numerical results obtained in this paper have important theoretical significance for the development of new heating methods in subsequent practical projects.

## 2. Modeling

### 2.1 Physical Models

Because the fuel truck tank for the axisymmetric structure, and some accessories on the tank, such as manholes, inlet and outlet ports, floating roof rows, etc. on the tank heat dissipation impact is small. The actual physical model is simplified as follows: the actual tank is simplified to a two-dimensional physical model, and assuming that the longitudinal thickness of the tank wall is the same, the thickness of the tank wall is 6mm, the length of the tank body is 2400mm, the height is 1300mm. the tank body material is 5083 aluminum alloy, the fluid in the tank is -50# diesel fuel, as shown in Figure 1.

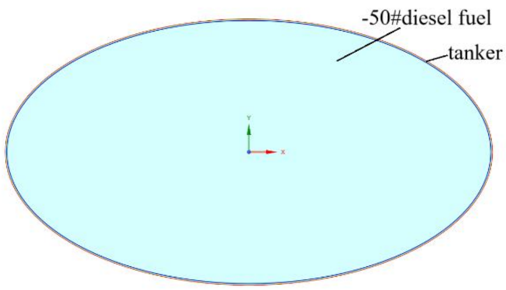



**Figure 1. Tank and Fuel Model**

Because of the extremely low ambient temperatures in the polar regions, which are much lower than the temperature of the fuel in the tanks, as well as the effects of air movement and solar irradiation, all these factors may have an impact on the heat transfer of the fuel in the tanks. There are three types of heat transfer: heat conduction, convective heat transfer and thermal radiation, and any energy transfer process is carried out in these three ways, and in many cases all three types of heat transfer work together in actual heat transfer problems. Since the temperature of the polar environment is very low in this study, the effect of thermal radiation is not considered in the analysis, and only convective heat transfer and heat con-duction are studied.

Fuel truck tank wall surface and the outside air direct contact, due to the existence of temperature difference between the flow of solid will produce heat transfer in the flow of solid intersection surface, the formation of convective heat transfer in the tank wall surface; tank wall surface and the tank wall near the direct con-tact with the fuel oil, fuel oil in the tank, the heat will be from the part of the temperature of the high temperature to the temperature of the part of the transfer of the low-temperature, at this time, the inner wall of the tank body for the natural way of convection heat transfer and heat conduction, and fuel oil in the tank heat transfer In this case, the heat transfer from the inner wall of the tank is a combination of natural convection heat transfer and heat conduction, while the heat transfer from the fuel inside the tank is also a combination of convection heat transfer and heat conduction. The strength of convective heat transfer capacity through the convective heat transfer coefficient to characterize, it is to describe the convective heat transfer is an important parameter of the degree of intensity, in dealing with convective heat transfer problems, how to determine the convective heat transfer coefficient and determine the model of convective heat transfer is the key factor in the study of this type of problem. According to the influencing factors of convective heat transfer, it can be categorized into forced convection, natural convection, mixed convection and other types, the heat transfer between the outer wall surface of the tank and the air studied in this paper belongs to the forced convection, while the heat transfer between the inner wall surface of the tank and the fuel belongs to the natural convection.

## 2.2 Mathematical Modeling

Simplified model for the calculation of the following assumptions.

(1) Neglect the local temperature difference caused by the tank walls on both sides of the axial direction, and consider the axial temperatures to be equal, so that the three-dimensional problem is transformed into a two-dimensional axisymmetric problem, and the temperature and velocity fields in a cross-section are studied.

(2) The tank walls around the tank are in direct contact with the outside air.

(3) The tank wall, tank bottom and tank top are treated as uniform equal-thickness plates, and the fuel in the tank is in full load condition, ignoring the presence of inert gas in the tank top area.

The steady-state thermal conductivity of the fuel in the tank through the tank wall is calculated as.

$$Q = \frac{\lambda A \Delta t}{\delta} \quad (1)$$

Where $Q$ is the convective heat transfer, W; $\lambda$ is the coefficient of thermal conductivity, W/(m·K); A is the convective heat transfer area, $\Delta t$ is the temperature difference between the fluid and the wall surface, K. The tank is in direct contact with the polar environment, the main form of heat exchange between them is convective heat transfer, which is the third type of boundary conditions.

The outer wall of the tank is in direct contact with the polar environment, and the main form of heat exchange between them is convective heat transfer, which is the third type of boundary conditions, and the equations are as follows:

$$-\lambda \frac{\partial T}{\partial n}|_{\Gamma} = h\left(T_{guan} - T_{air}\right) \quad (2)$$

Where, $\lambda$ is the thermal conductivity of the tank material, W/(m·K); $h$ is the convective heat transfer coefficient between the outside air and the wall of the tank, W/(m$^2$·K); $T_{guan}$ is the temperature of the tank, K; $T_{air}$ is the temperature of the polar ambient, K; and $\Gamma$ is the boundary (the surface of the outer wall of the tank).

Since the fuel oil temperature drop is a non-stationary process, a non-stationary analysis is required. Therefore, the numerical method used in this paper is to discretize the control equations in space and time. The fluid motion conforms to the basic conservation laws: the law of conservation of mass, the law of conservation of momentum and the law of conservation of energy.

Mass Conservation Equations:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0 \quad (3)$$

Where, $\rho$ is the fuel density, kg/m$^3$; $t$ is the transient temperature drop time, s; $x, y$ are the coordinate axes under the right-angle coordinate system, m; $u, v$ are the components of the fuel flow rate in the direction of the $x, y$ coordinate axes, m/s.

Momentum conservation equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho uu)}{\partial x} + \frac{\partial(\rho vu)}{\partial y} = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial y}\left[\eta\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)\right] \quad (4)$$

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho vv)}{\partial y} = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial x}\left[\eta\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)\right] + \rho g \quad (5)$$

where $\eta$ is the fuel power viscosity, Pa·s.

Energy conservation equation:

$$\frac{\partial(\rho c_p T)}{\partial t} + \frac{\partial(\rho u c_p T)}{\partial x} + \frac{\partial(\rho v c_p T)}{\partial y} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda \frac{\partial T}{\partial y}\right) \quad (6)$$

Where $c_p$ is the constant pressure specific heat capacity of the fuel, J/ (kg·K), $T$ is the instantaneous temperature of the fuel, K; λ is the thermal conductivity of the fuel, W/ (m·K). Considering the effect of natural convection, it is necessary to set the gravitational acceleration g=-9.81m²/s in the Y direction within the computational model, and at the same time, the density setting of the fuel oil is chosen to be the Boussinesq assumption, which only needs to consider the density change in the buoyancy term in the momentum equation, and the density is a constant in the other equations.

Boussinesq hypothesis:

$$\rho_\infty - \rho = \rho\alpha(T - T_\infty) \quad (7)$$

Where $\rho_\infty$ is the density of the fuel at the initial temperature, kg/m$^3$; $\alpha$ is the volume expansion coefficient of the fuel, 1/K; $T_\infty$ is the initial temperature of the fuel, K.

The formula for the volume expansion coefficient α is:

$$\alpha = -\frac{1}{\rho}\left(\frac{\partial\rho}{\partial T}\right)_p \quad (8)$$

Wax phase transition modeling:

FLUENT solves the flow and heat transfer problems of Solidification/Melting by the enthalpy-porosity method without tracking the positional changes of the phase interface. The model area is divided into solid, mixed, and liquid zones. The solid-liquid mixed zone is treated as a porous medium zone, and the percentage of fluid is regarded as the porosity, i.e., the fraction of liquid phase in the grid cell. During the liquid fuel cooling and solidification process, the porosity decreases continuously from 1 to 0. The volume ratio of the liquid phase fuel (liquid phase fraction $\beta$) is expressed in terms of temperature.

$$\beta = \begin{cases} 0, T < T_S \\ \frac{T - T_S}{T_L - T_S}, T_S < T < T_L \\ 1, T > T_L \end{cases} \quad (9)$$

Where $T_S$ is the solid-phase line temperature, K, and $T_L$ is the liquid-phase line temperature, K.

Considering the natural convection formed during the fuel solidification process due to the change in the density of the fuel, the source terms of the momentum and energy equations are corrected, and the expressions are as follows:

Energy equation source phase:

$$S_h = \frac{\rho}{c_p}\frac{\partial(\Delta H)}{\partial t} \quad (10)$$

Momentum equation source phase:

$$S_u = \frac{(1-\beta^2)}{\beta^3+\varepsilon}A_{mush} \quad (11)$$

$$S_v = \frac{(1-\beta^2)}{\beta^3+\varepsilon}A_{mush}v + \rho_{ref}g\alpha(t - t_{ref}) \quad (12)$$

Where, $\rho$ is the fluid density, kg/m$^3$; $c_p$ is the specific heat capacity, J/(kg·K); $\beta$ is the liquid phase rate; $\varepsilon$ is the number less than 0.0001, preventing the denominator of the formula is zero; $A_{mush}$ is the number of consecutive fuzzy regions, the general value of $10^4$-$10^7$; $\alpha$ is the volume expansion coefficient of fluid, K$^{-1}$; $t_{ref}$ is the base temperature (initial temperature), K; $\rho_{ref}$ is the the density of the fluid at the reference temperature, kg/m$^3$.

## 3. Numerical Simulation Calculations

### 3.1 Grid Division

As shown in Figure 2, the computational domain is divided into a two-dimensional tetrahedral mesh using ANSYS/mesh. The tank is in direct contact with the outside air for convective heat transfer, which in turn affects the temperature field distribution of the oil inside the tank. Considering the grid cell size of the solid domain (tank) and the fluid domain (fuel inside the tank), the results of the numerical simulation are affected by the mesh cell size of the solid domain (tank) and the fluid domain (fuel inside the tank). In order to accurately capture the temperature and phase distribution, the mesh is encrypted locally in the tank region and the mesh-independence verification is carried out. In order to ensure the accuracy of the calculation and to save the cost of calculation, the grid size of 1mm in the solid domain and 30mm in the fluid domain is used for the calculation.

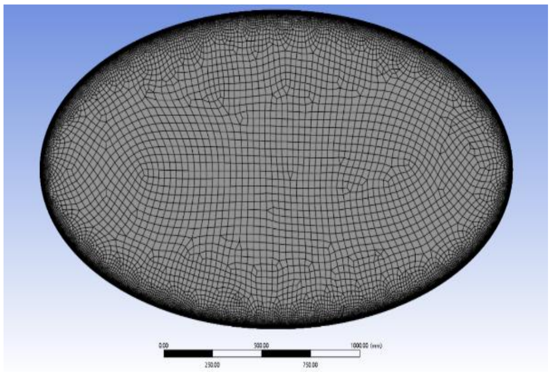


**Figure 2. Tank and Fuel Grid Model**

### 3.2 Initial Conditions

At the initial moment of calculation, the tank is filled with liquid -50# diesel fuel, and the temperature of diesel fuel is set to the average annual temperature of Antarctic Taishan Station -35°C. In addition, the physical parameters of diesel fuel and other materials involved in this paper are shown in Table 1.

**Table 1. Physical Properties of Fuel and Related Materials**

| parameters | numerical value |
|---|---|
| -50# Diesel density(20 °C)/(kg/m$^3$) | 790～840 |
| kinematic viscosity(20 °C)/(mm$^2$/s) | 1.8～7.0 |
| dynamic viscosity | udf |
| cold filtration point /°C | ≤-44 |
| freezing point /°C | ≤-50 |
| specific heat capacity /(J/(kg·K)) | 1900 |
| Liquid thermal conductivity /(W/(m·K)) | 0.13 |
| Solid State Thermal Conductivity /(W/(m·K)) | 1.16 |
| latent heat of phase transition /(J/g) | 200 |
| coefficient of thermal expansion /(1/K) | 0.0008 |
| 5083 Aluminum Alloy (Tank) Density /(kg/m$^3$) | 2660 |
| specific heat capacity /(J/(kg·K)) | 947 |
| thermal conductivity /(W/(m·K)) | 117 |

### 3.3 Boundary Conditions

In the fuel truck tank fuel heat transfer analysis, the external environment and the tank wall surface of the heat transfer parameters can not be quantitatively characterized by numerical values, due to the extremely low temperature of the polar environment and the impact of wind speed, the fuel truck in the stationary storage will be subject to the role of the air flow rate, this convective heat transfer belongs to the forced convection, in order to more realis-tic response to the fuel truck in the polar environment of the tank's convective heat transfer, so this paper selects the means of simulation to Simulation to calculate the convective heat transfer coefficient.

The fuel tank of the fuel truck is in direct contact with the outside air, and the wind speed is 3.9m/s (annual average wind speed of Kunlun Station), the ambient temperature is -70°C, and the heat transfer mode is forced convection heat transfer mode. Using Solid-works software to establish a good gasoline truck body model, mesh the fluid domain model shown in Figure 3, select the AN-SYS/CFX module to carry out the calculation of convective heat transfer coefficient of the tank wall.

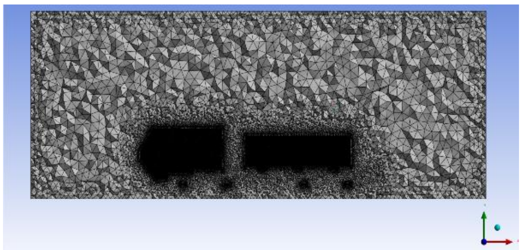


**Figure 3. Calculation Model of Convective Heat Transfer Coefficient after Grid Division**

The method adopted in this paper is to set the air inlet in the direction of the front of the vehicle to simulate the inflow of air from the polar environment, and set the air outlet in the direction of the rear of the vehicle and the surrounding area to simulate the outflow of gas, and the air velocity is set to 3.9 m/s. The temperature is -70°C. The convective heat transfer coefficient is calculated after setting the corresponding boundary conditions.

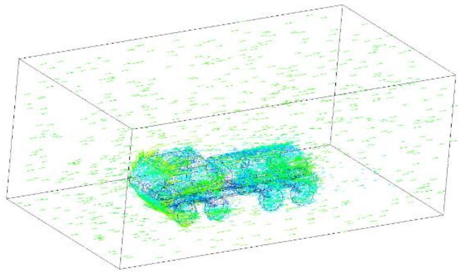


**Figure 4. Gas Flow Rate Cloud for Refueling Trucks in Polar Environments**

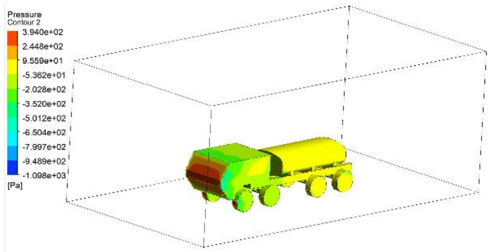



**Figure 5. Cloud Diagram of Pressure Distribution of Refueling Trucks in Polar Environments**

As can be seen in Figures 4, 5, it can be seen that the air flow rate and pressure in the tank section is less due to the shading of the front part of the vehicle. The convective heat transfer coefficient of the fluid at the wall of the tank is extracted and the result is shown in the figure 6, the convective coefficient be-tween the outer wall of the tank and the air is about 22.8 W/(m2·K).

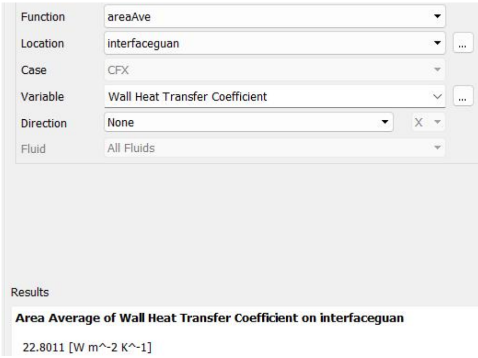
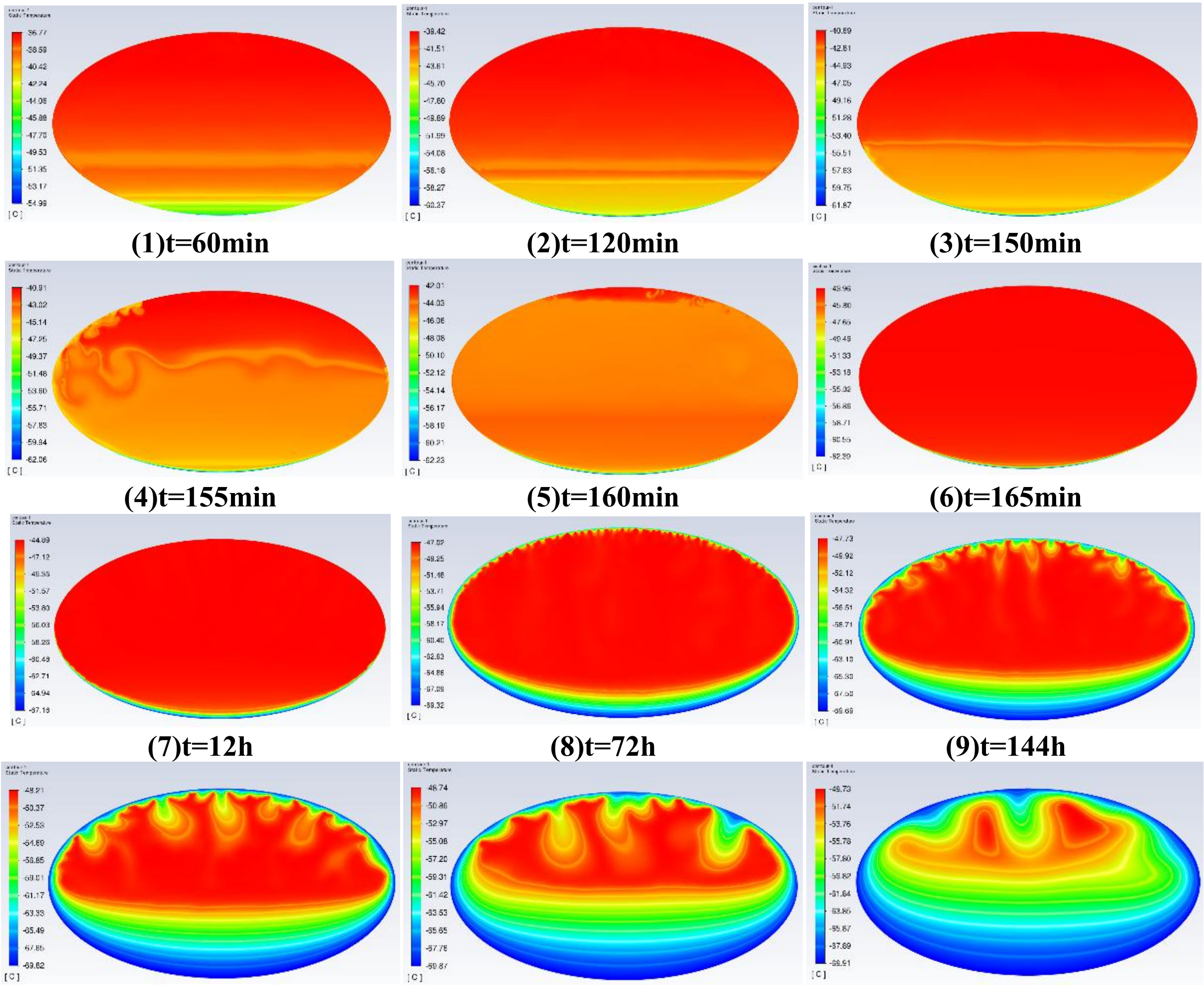



**Figure 6. Convection Heat Transfer Coefficient of Fuel Truck Tank Wall**

Select the separation solver, two-dimensional unsteady mode, use the default reference pressure setting of FLUENT and turn on the gravity option, set the flow as laminar, select the pressure-velocity coupling method and PRESTO! pressure interpolation method, and turn on the solidification and melting model.

## 4. Analysis of Simulation Results

### 4.1 Distribution of Fuel Oil Temperature Field in Tanks with Time



**(1)t=60min** **(2)t=120min** **(3)t=150min**

**(4)t=155min** **(5)t=160min** **(6)t=165min**

**(7)t=12h** **(8)t=72h** **(9)t=144h**

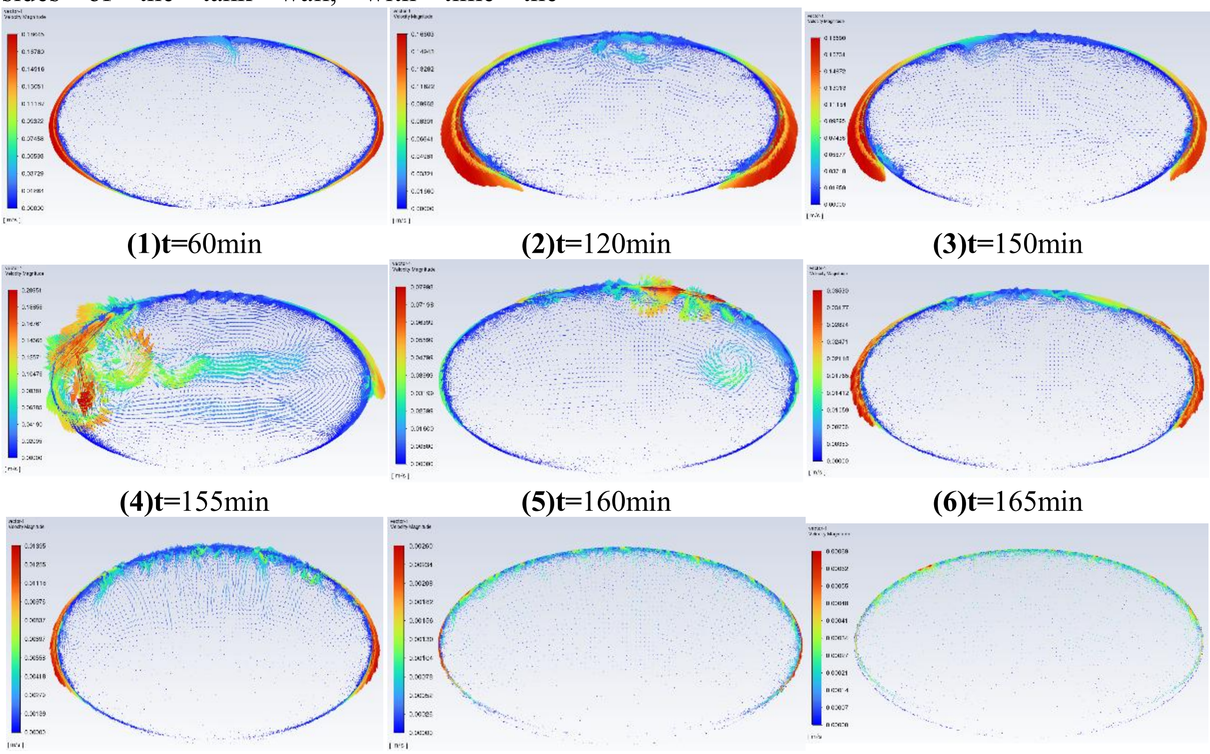
**(10)t=216h** **(11)t=288h** **(12)t=360h**

**Figure 7. Temperature Field Variation with Time during Fuel Solidification Process**

Fuel temperature field change rule:

Figure 7 for the fuel truck tank fuel temperature distribution map, in 60 min, the fuel temperature field bottom region appears obvious temperature gradient, the upper region temperature distribution is more uniform, the fuel temperature is about -36℃, the lowest temperature appears in the tank bottom near the wall area, for -53.9℃ or so, the fuel heat exchange began and concentrated in the tank bottom wall, near the wall at the liquid oil temperature continues to decrease, and then and the upper liquid oil Continuous heat transfer, the temperature field from the bottom upward from low to high laminar distribution, with time upward progression; in 150 min, the fuel temperature field shows obvious upper and lower parts of the stratification, the upper fuel temperature of about -40℃, the lower fuel temperature of about -44℃; in 155 min, the fuel temperature field from the gradient distribution of the first smooth upward progression changes, near the tank left wall surface of the middle and upper region Temperature field appeared irregular vortex-like distribution, and this distribution trend from the left to the right to pass; in 165 min, the lowest temperature field appeared in the bottom area of the tank, about -62℃ or so, the tank fluid temperature field from the previous gradient distribution into a non-obvious layered state, at this time most of the fuel temperature of -44℃, and after the change in the temperature field is mainly concentrated in the tank bottom and the two sides of the tank wall with the After that, the temperature field change mainly focuses on the bottom and both sides of the tank wall, with time the temperature gradient at the bottom and both sides of the tank wall continues to the upper and both sides of the extension; 72h, the fuel temperature field in the tank top region also appeared in the gradient distribution, the whole wall of the tank to form a large encircling gradient distribution, and the trend of the bottom of the tank is obviously stronger than the top of the tank. There is no obvious change in the fuel temperature field within the encircling circle; after that, the temperature field distribution shows a trend of contraction from the surrounding area of the tank wall to the center, and a downward vortex distribution of the fuel appears in the top area of the tank.

### 4.2 Fuel Velocity Field Distribution with Time



**(1)t=**60min **(2)t=**120min **(3)t=**150min

**(4)t=**155min **(5)t=**160min **(6)t=**165min

**(7)t=**4h **(8)t=**8h **(9)t=**12h

**Figure 8. Velocity Field as a Function of Time during Fuel Solidification**

Fuel velocity field change rule:

Figure 8 for the fuel truck tank fuel velocity vector distribution, tank fuel due to heat transfer temperature gradient leads to different density and then appear in the center of the fuel from the bottom up, tank wall at the fuel sinking, tank internal vortex formation, natural convection occurs in the tank. In 60 min, the velocity field in the flow velocity of the largest region is mainly distributed in the tank on both sides of the lower wall, then the maximum flow velocity region from the lower part of the tank wall along the tank wall upward movement, and finally concentrated in the top region, the tank liquid shows different sizes of vortex flow state, and the upper part of the tank vortex state is more obvious, with the time the bottom of the tank near the wall at the flow velocity with the time is more and more small, accompanied by the bottom part of the tank Fluid flow rate is also getting smaller and smaller, the flow state becomes worse, and finally completely lose the mobility; in 155min, the velocity field changes drastically compared with the previous, the left side of the tank near the upper wall of a large vortex flow, the direction of the flow field from the left side of the vortex area to the right, the upper and middle areas of the flow rate increased significantly compared with the previous; in 160 min, the velocity field by the previous left side of the vortex flow to the top of the tank to the right side of the region, and the formation of In 165 min, the flow field in the tank is mainly distributed in the upper part of the tank, and the region with the largest flow velocity is mainly distributed at the top of the tank and both sides of the wall, and the flow velocity is getting smaller and smaller with time.

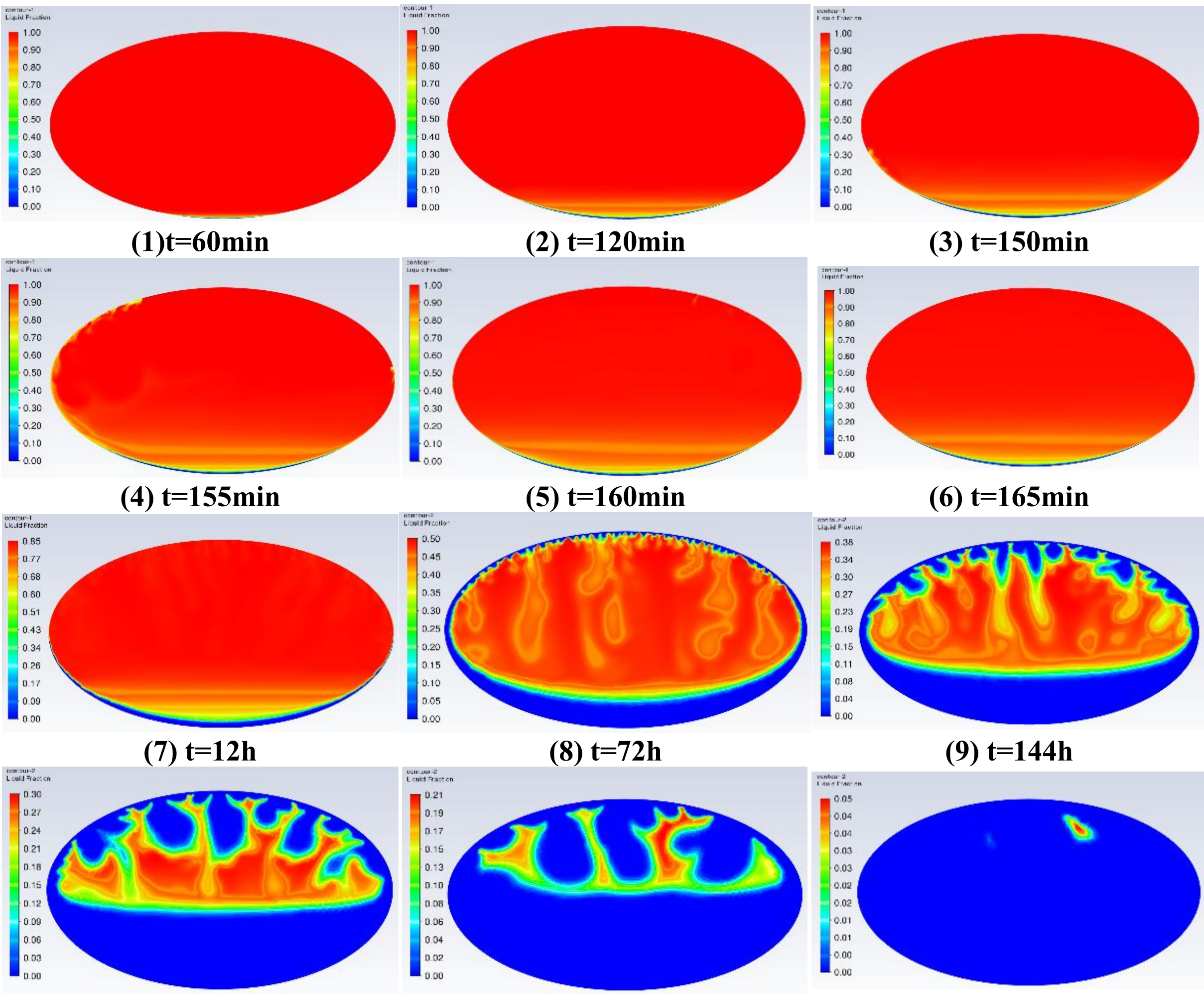
In the whole storage stage, the top vortex area is sinking because of the increase of fuel density in the cooling area, forming several different vortex areas; the lower vortex area is close to the two sides of the tank wall because of the maximum velocity of the fuel flow, and the fuel near the bottom of the tank wall is coagulated and precipitated. The longer the time, the lower part of the region of the fuel temperature difference is smaller, as shown in the figure, the bottom part of the fuel part of the tank no longer flow, the lower part of the region of the flow rate can also be considered as basically zero, only in the top of the tank of gasoline trucks to form a few smaller vortex area, 24h after the fuel flow field is only distributed around the wall, the maximum flow rate is less than 1mm/s, at this time, the oil flow rate has been very small, the role of natural convection has disappeared basically.

### 4.3 Phase Transition Interface Changes during Fuel Solidification Phase Transition Process

Fuel solidification phase change process phase change interface change rule:

Figure 9 for the fuel truck tank fuel solidification phase change process phase change interface changes, the red area in the figure represents the liquid phase, the blue area rep-resents the solid phase, the other color area for the paste area, represents the solid-liquid phase interface. From the solidification process of the phase transition interface in different moments of the distribution of the initial tank fuel from liquid to solid process is very slow, liquid-solid phase transition first appeared in the bottom of the tank near the wall area, and then to the bottom of the tank on both sides and the upper part of the extension of the transformation, in the phase transition process can be clearly seen, the bottom of the tank fuel solidification layer thickness is significantly greater than the two sides and the upper part of the region. The temperature distribution of the fuel oil in the first period is also a laminar trend, and the temperature in the upper part of the tank is higher than the temperature in the lower part of the tank. The thickness of the condensate layer in each direction is different, the temperature of the laminar distribution, the main reason is that the fuel truck tank fuel temperature is higher than the external ambient temperature of the tank, the tank near the wall surface of the fuel first with the outside world to occur heat exchange, so that the fuel truck tank fuel temperature difference, the fuel inside the tank because of the high temperature, density is small, due to the buoyancy and rise, close to the wall surface of the tank at the fuel due to the low temperature, density, and then sink, which causes Fuel oil in the tank to form a natural convection. In the early stage of solidification, the liquid components in the phase change region is more, there is a certain natural convection phenomenon, with the solidification of the phase change process, the natural convection gradually weakened, the phase change region of the form of heat transfer into a solid heat conduction is dominated. The overall solidification trend is first from the bottom of the tank upward progression, after the top of the tank area is also solidified around the formation of a large irregular circle, the solidification process of the encirclement circle continues to shrink, until completely solidified.

Combined with different moments of fuel temperature field, velocity field and solidification phase change process changes, the fuel in the tank in the early phase of solidification phase change heat transfer to natural convection is the main, this stage of the fuel temperature drop faster, in the fuel temperature down to its condensation point -44℃, then the fuel began to phase waxing, the velocity field flow rate decreases dramatically, the natural convection process gradually disappeared; and after the heat transfer to heat conduction is the main, the fuel temperature drop rate at this stage is greatly slowed down. The temperature drop rate slows down dramatically at this stage.



(1)t=60min (2) t=120min (3) t=150min

(4) t=155min (5) t=160min (6) t=165min

(7) t=12h (8) t=72h (9) t=144h

(10) t=216h (11) t=288h (12) t=360h

**Figure 9. Interfacial Changes of Phase Transition during Fuel Solidification**

**4.4 Analysis of Data Results**

In order to study the variation of -50# diesel oil temperature with time at different locations in the tank, five characteristic points were selected in the tank for comparison, and the co-ordinates of each point were as follows: point A (0, -600), point B (0, -300), point O (0, 0), point C (0, 300), and point D (0, 600), as shown in Figure 10:

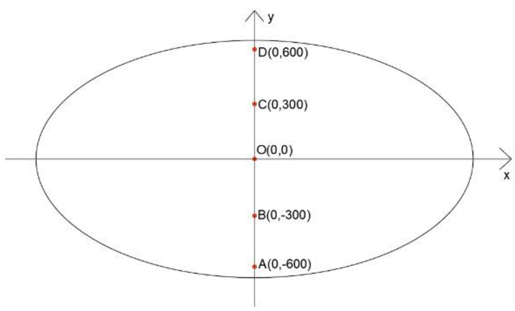



**Figure 10. Schematic of Feature Point Selection**

Figure 11 shows the temperature drop curve of the selected feature points with time, it can be seen that, in this stage of the fuel temperature drop in the process of the temperature distribution of each feature point is characterized by a decrease in order from top to bottom, in which the temperature drop rate at point A is much greater than the rest of the position, the temperature drop curve of the other feature points has a similar trend, and the temperature drop rate of each feature point from the initial -35°C began to drop to -44°C after the temperature drop rate becomes very slow, and the A, B, O, C, D points from the initial temperature drop to -44°C time were 1h, 2.42h, 2.58h, 2.67h, 2.75h, it can be found that the temperature drop time of each characteristic point increases in turn, the time required at point A is significantly lower than the rest of the points, which is due to the initial stage of the external ambient temperature on the fuel near the wall of the tank has a greater impact, while the fuel tanks away from the wall of the tank area by the ambient temperature has less impact, and at the same time because of the Tank heat transfer temperature gradient, the fuel inside the tank natural convection, natural convection heat transfer makes the low temperature fuel deposited in the tank bottom area, while constantly generate upward flow in the tank top area to form a vortex, so near the tank bottom wall at point A fuel temperature is much lower than the other locations, and away from the bottom of the tank region at each point shows the higher the higher the temperature of the characteristics of the region.

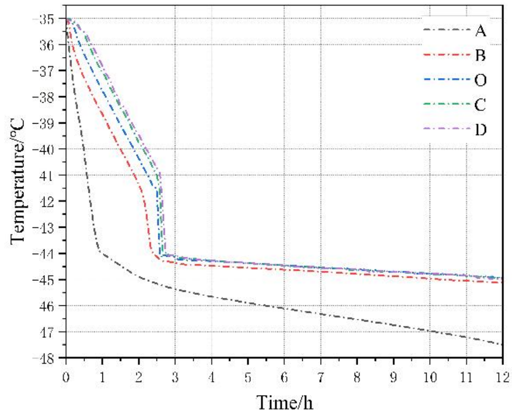



**Figure 11. Variation of Average Temperature of Fuel Oil in Tanks with 12h Storage**

From Figure 11, it can be found in O, C, D characteristic point temperature drop curve in about 2.5h when the trend of a large change, it is necessary to carry out a detailed analysis of this time period (150min-165min), the time period of the characteristic point temperature and speed changes as shown in Figure 12, 13:

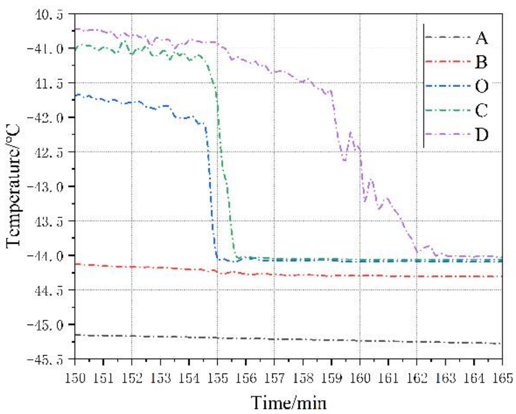



**Figure 12. Temperature Variation at Different Feature Points**

Combined with the temperature and velocity changes at different characteristic points and velocity vector diagrams at this time, it can be found that from 155 min onwards, the velocity at characteristic points O, C, D increased significantly compared with the previous one, the vortex intensity of the flow field increased, and the fuel in the middle and upper part of the tank was fully involved in the heat exchange, which led to most of the fuel in the upper part of the tank cooled down to -44℃ in just 10min, and after that the temperature drop rate slowed down dramatically, and the temperatures of the characteristic points A, B decreased slowly in the temperature gradient of -44.2℃ and -45.2℃, respectively. 44.2℃ and -45.2℃ slowly, from Figure 10 can be found in the characteristic point temperature are reduced to -44℃ after the characteristic point velocity is almost zero, so the fuel flow velocity directly affects the distribution of fuel temperature gradient, that is, the natural convection heat transfer significantly affect the temperature distribution of fuel in the tank, and in the tank fuel temperature is lower than -44℃, the natural convection in the tank gradually disappeared, and thereafter the heat transfer to the Thereafter, heat transfer is dominated by heat conduction.

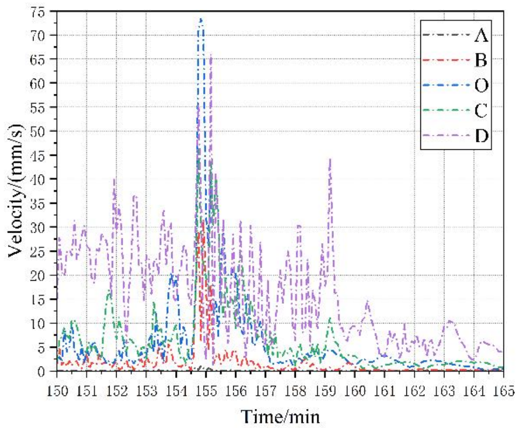



**Figure 13. Velocity Variation at Different Feature Points**

As can be seen from Figure 14, in the whole process near the bottom of the tank characteristic point A temperature drop rate is much larger than the rest of the points, while the rest of the position of the characteristic point temperature in the -44 ℃ down to the temperature drop curve is almost synchronous changes, 72h after the temperature drop curve of the various points change, near the top of the tank of the C, D temperature drop process there is a tendency to fluctuate up and down, and the D point of temperature fluctuations are more frequent, and the rest of the position of the temperature drop process for the gradual decline in the tendency; the tank fuel oil After complete solidification, the temperature of each characteristic point is O>C>B>D>A, and the lowest temperature point is located near the bottom of the tank at point A and the top of the tank at point D, which is very different from the sequential arrangement of D>C>O>B>A in Figure 11 Summarizing the characteristics of the above temperature distribution, combined with the fuel oil temperature and velocity field at different moments and the solidification phase transition process diagram, we analyze the reason for this is that after the fuel oil temperature is reduced to -44℃, the velocity of the flow field is greatly reduced. The reason is that after the fuel temperature drops to -44℃, the velocity of the whole flow field decreases greatly, the natural convection heat transfer decreases significantly, and at the same time, the fuel waxing phase change releases a large amount of latent heat, leading to a significant slowdown in the temperature drop process; 72h, the fuel in the top area of the tank is solidified, and the solidified area on both sides of the tank bottom and tank wall forms an encircling circle, and the encircling circle is gradually contracted by the phase change afterwards, and the liquid fuel inside the circle is gradually reduced until it is completely solidified. In the process of solidification phase change, the phase change interface near point C, D changes with time, resulting in a fluctuating downward trend of its temperature.

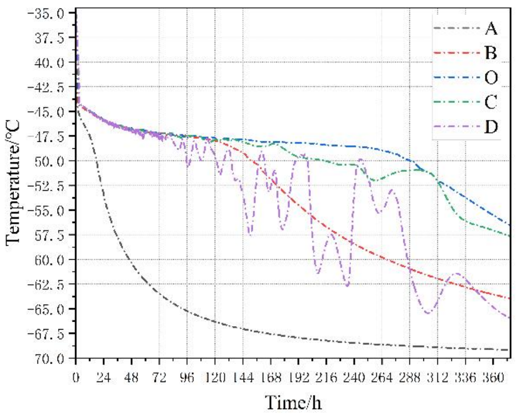



**Figure 14. Temperature Variation of Each Characteristic Point during the Whole Process of Fuel Oil Solidification in Tanks**

As can be seen from Figure 15, the fuel solidification speed in the early stage is faster, 48h when the tank fuel liquid phase rate of 46%, about 1.125% of the fuel solidified per hour, at this time the tank fuel has been solidified in half, after the solidification speed slows down, 216h tank fuel liquid phase rate of 9.8%, in the 48-216h stage of solidification of about 0.215% of the fuel per hour, in the subsequent stage of the remaining less than 10% of liquid Fuel oil, but the solidification time of more than one hundred hours, analyze the reason is that the fuel oil near the wall surface of the tank in the early period through the tank wall plate and the outside low-temperature airflow heat ex-change, the fastest temperature drop, the first solidification, solidification speed is faster, with the fuel oil around the tank wall is gradually cooled, the solidification of the phase transition from the 72h solidification of the interfacial distribution of the solidification can be seen throughout the wall of the tank appeared to be a solidified layer, the formation of an encompassing circle structure, wrapped around the circle with liquid fuel oil, the liquid fuel oil, the liquid fuel oil, and the liquid fuel oil, the liquid fuel oil, and the liquid fuel oil. In the tank around the inner wall precipitation of a certain thickness of paraffin layer thermal conductivity compared with the tank wall plate is very small, equivalent to the formation of a layer of thermal insulation at the inner wall of the tank, and at this time the fuel oil in the tank heat transfer mode of thermal conductivity based on the fuel oil temperature decline slows down, solidification rate slows down.

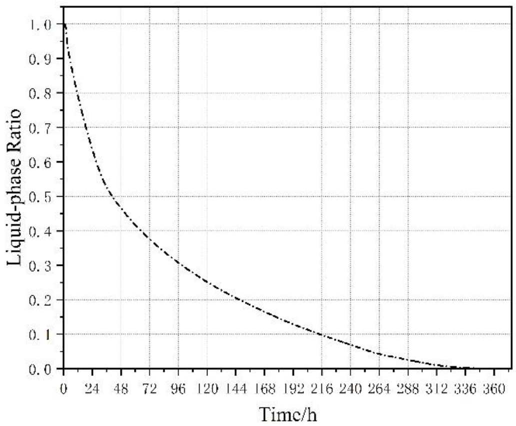



**Figure 15. Change Curve of Liquid Phase Fraction of Fuel Oil in Tank**

## 5. Conclusion

In this paper, numerical simulation of temperature drop solidification process of fuel truck tank fuel in polar environment was studied by using ANSYS/FLUENT software, and focused on analyzing the temperature distribution and flow field changes of fuel in the tank and the distribution of solidified oil layer, and the conclusions are as follows:

(1) The temperature field at the beginning of the process shows a stratified distribution from the bottom upward from low to high, after the fuel temperature is lower than -44℃, the temperature field becomes a non-obvious stratified distribution, and there is an obvious gradient distribution only at the bottom of the tank and on both sides of the tank wall, which is slowly extended to the upper part of the tank and the two sides with the passage of time, and there is also an obvious gradient distribution in the tank top area, after which the whole wall of the tank forms a large encircling gradient distribution, and the distribution of the temperature field afterward shows a tendency to shrink to the middle by the wall, and the distribution of the temperature field is reduced to the top of the tank. After that, the temperature field distribution shows a trend of contraction from the tank wall around the middle, the fuel oil in the tank top area appears downward vortex distribution, and finally the whole tank fuel oil temperature field shows a laminar and fossilized gradient distribution.

(2) From the initial to the fuel temperature is lower than -44℃, the natural convection heat transfer dominates, the fuel temperature field distribution changes with the velocity field, after the natural convection is significantly weakened, this time the fuel temperature is mainly subject to heat conduction, but the fuel temperature drop rate is significantly reduced compared with the previous.

(3) In the polar environment fuel tank fuel storage about 2.75h tank fuel temperature is lower than -44 ℃, this time the fuel state has been unable to meet the requirements of the vehicle use, storage of about 374.75h tank fuel completely solidified, solidification of the regional temperature is gradient distribution. Solidification process from the tank wall around the encircling type with time irregular to the inner contraction.

(4) The simulation results in the fuel temperature drop process of temperature distribution and change rule and the distribution of fuel solidification area can be applied to the polar environment of the fuel truck tank fuel insu-lation heating program design to provide some theoretical guidance.

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