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Mathematical modeling of large floating roof reservoir temperature arena

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The current study is a simplification of related components of large floating roof tank and modeling for three dimensional temperature field of large floating roof tank. The heat transfer involves its transfer between the hot fluid in the oil tank, between the hot fluid and the tank wall and between the tank wall and the external environment. The mathematical model of heat transfer and flow of oil in the tank simulates the temperature field of oil in tank. Oil temperature field of large floating roof tank is obtained by numerical simulation, map the curve of central temperature dynamics with time and analyze axial and radial temperature of storage tank. It determines the distribution of low temperature storage tank location based on the thickness of the reservoir temperature. Finally, it compared the calculated results and the field test data; eventually validated the calculated results based on the experimental results.

Keywords: floating roof tank, temperature field, natural convection, numerical simulation.

INTRODUCTION

In view of rising oil dependency and consumption, establishment of the large national oil reserves have becomes an important part of each country. Oil tanks are mostly floating roof tanks; the accurate prediction of the temperature field of large floating roof tank is of great significance for strategic and commercial reserve of crude oil. In the process of crude oil in storage tank, heat transfer will occur in crude oil through the tank roof, wall and bottom soil because of temperature differences between the crude oil tank and the external environment. When the temperature of the crude oil tank is dropped to freezing point, it is easy to cause the blockage of tank internals to cause the production accidents. In order to solve the problem of reduced temperature of crude oil in oil tank, usually crude oil tank heating temperature is required. Because of the large floating roof tank oil storage for a longer time periods, difficulties are encountered for maintenance of crude oil heating temperature design and calculation. Therefore, accurate grasping the change of temperature drop in the process of oil in storage[1–3] has important practical significance for storage process design of large floating roof tank and ensuring the safety of oil depot and economical operation.

Giving priority to experimental research and numerical simulation for large floating roof tank oil temperature field is quite practical. Oliveski[4, 5] analyzed the natural convection and thermal stratification of crude oil within the tank through experimental tests and numerical simulation to get the temperature field of crude oil tank. Results were compared with the test data to get the storage tank temperature drop of oil in the tank wall. In the meantime, Oliveski[6, 7] studied the natural convection cooling process in the hot water storage tank[8–12] and established correlation between Nusselt number (Nu) and storage tank volume, radius, height in the fluid unsteady process. Rodriguez[13] and Fernandez-Seara[14] simulated the initial static storage of natural convection cooling fluid transient process to the vertical cylindrical hot water storage tank[15–18] using the finite volume method. Dimensionless number was given in relation to the tank of crude oil temperature drop process; finally the relation between Nu and the average temperature of fluid was established. Mawire[19] developed a small non-insulated tank model to quantitatively evaluate the thermal stratification of the tank model during the loading and unloading process. At the same time, the mathematical model of the tank thermal distribution was established according to the energy balance equation.

Yu Da[20, 21] developed the temperature monitoring system of large floating roof tank using the thermistor element and made special temperature measuring device to monitor the temperature of large floating roof tank. Vertical temperature distribution inside the tank oil curve was drawn and analyzed the shape of the tank of crude oil, temperature drop process, condensation product of crude oil wax process and the influence of condensate oil to the temperature drop. Li[22] established a two-dimensional large floating roof tank temperature field model of condensate oil to study the influence of the temperature drop on the basis of establishing natural convection and the influence of atmospheric temperature, insulation layer thickness on the tank wall, physical properties of soil at the tank bottom and physical properties of oil. Solution algorithm was developed which coupled floating cabin area, oil product area, soil region, tank wall, thermal insulation layer and compared the calculated results with the field test data.

The problem associated with temperature drop of crude oil in the tank, in essence, is owned by the unsteady natural convection cooling process of the fluid in the cylindrical structure[23, 24]. The accurate prediction of the temperature field of a large floating roof tank is of great significance to storage design of large floating roof tank which ensures the safe operation of an oil depot. Considering the influence of atmospheric temperature, physical properties of oil and the tank wall insulation layer thickness on the temperature field of crude oil in storage tank; the objectives of current study was to simplify related components of large floating roof tank and modeling for three dimensional temperature field of large floating roof tank.

MATHEMATICAL MODELING

Buoyancy Driven Flow

There is a fluid flow of temperature drop process of crude oil in oil tank which is not a single fluid thermal conductivity involving flow problem. Its flow equation is an important link necessarily of oil tank temperature drop mathematical model. There is the detailed introduction to the flow equation of crude oil storage tank.

In the natural convection, the flow intensity is caused by buoyancy, which can be decided by Rayleigh number (Ra)[25, 26]:

$$Ra = \frac{g\rho\beta\Delta TL^3}{\mu\alpha} \tag{1}$$

Among them, the β for the thermal expansion coefficient:

$$\beta = -\frac{1}{\rho}\left(\frac{\partial\rho}{\partial T}\right)_p \tag{2}$$

α for thermal diffusivity (temperature conductivity) is:

$$\alpha = \frac{k}{\rho c_p} \tag{3}$$

When the fluid is heated and its density changes with temperature, density changes caused by gravity difference will cause the flow of the fluid. When simulating natural convection in closed area, calculation results will depend on the fluid quality computing area. Unless the density is known, we can't determine the fluid quality, so, for increased natural convection flow. Boussinesq model can be used to get a better convergence rate which is faster than set density as a function of temperature to solve the problem. As long as the true density change is very small, the approximation is very accurate.

$$(\rho - \rho_0)g \cong -\rho_0\beta(T - T_0)g \tag{4}$$

where: ϱ is density, kg · m^{-3};g is gravity acceleration, m · s^{-2}; β is coefficient of thermal expansion, K^{-1}; α is thermal diffusivity, $m^2 \cdot s^{-1}$; c_p is specific heat capacity, J · $(kg \cdot K)^{-1}$; T is temperature, K; k is heat transfer coefficient of the fluid, W · $(m \cdot K)^{-1}$.

Governing Equations

The equation can be represented as follows[27, 28]:

1. Mass conservation equation

$$\frac{\partial\rho}{\partial t} + \mathrm{div}(\rho\vec{v}) = 0 \tag{5}$$

2. Momentum conservation equation

$$\frac{\partial(\rho v_i)}{\partial t} + \mathrm{div}(\rho v_i\vec{v}) = \rho\left(\frac{\partial v_i}{\partial t} + \vec{v}\cdot\mathrm{grad}v_i\right) \tag{6}$$

3. The equation of conservation of energy

$$\frac{\partial(\rho T)}{\partial t} + \mathrm{div}(\rho\vec{v}T) = \mathrm{div}(\frac{k}{c_p}\mathrm{grad}T) + \frac{S_T}{c_p} \tag{7}$$

where: $\boldsymbol{v}$ is velocity, m · s^{-1}; S_T is source term.

Boundary and Initial Conditions

While using the above three control equation, there is need to specify the boundary conditions, oil temperature drop of the large floating roof tank is a transient problem, so the initial conditions are given. This constitutes the temperature field simulation of large floating roof tank process with complete mathematical description.

1. Boundary conditions[29]

Tank top $\lambda_t\frac{\partial T}{\partial z} = h_t(T_f - T)$

Tank wall $\lambda_w\frac{\partial T}{\partial r} = h_w(T_f - T)$

2. Initial conditions

$$T|_{t=t_0} = T_0 \;,\; \rho|_{t=t_0} = \rho_0 \;,\; \vec{v}|_{t=t_0} = \vec{v}_0 \;,\; p|_{t=t_0} = p_0$$

Where: λ_t , λ_w are the coefficient of thermal conductivity of tank top and wall respectively, W · $(m \cdot K)^{-1}$; h_t, h_w are heat transfer coefficient of tank top and wall respectively, W · $(m^2 \cdot K)^{-1}$; r is radius of floating tank, m; z is height of floating roof, m.

Assumptions Simplify and Simulated Condition

The main ways of heat dissipation in the operation of the large floating roof tank include: through the tank wall heat transfer into the atmosphere, roof heat into the atmosphere and the soil thermal conductivity at the tank bottom. There are a number of influencing factors of large floating roof tank oil temperature drop; oil temperature drop of the large floating roof tank is a very complicated process. For the execution of convenient numerical simulation, following are the simplification and assumption[30–32]:

(1) Because the solar exposure is only a period during the day, the environmental temperature is the average temperature; so, ignoring the solar radiation effect of tank oil temperature drop, ignoring the radiation heat transfer between the sun and storage tank;

(2) Assuming that the plate thickness of the tank wall is uniform;

(3) Assuming that the thickness of the floating roof tank is consistent, translate the baffle plate of floating roof tank, the air layer into an equivalent import coefficient is simulated in order to simulate is convenient;

(4) Ignore the tank due to physical and chemical changes of crude oil heat source;

(5) Assuming that the storage tank of the initial temperature is uniform, and temperature at each position is consistent, do not consider the process of sending and receiving oil, there is a certain height of oil in the storage tank in initial stages.

According to the above simplifications and assumptions, large floating roof tank model was established. As shown in Figure 1. Simulation of floating roof tank radius of 48 m, tank liquid level height of 21 m, tank wall heat preservation material adopted double silicate insulation board insulation, insulation layer thickness of 0.08 m; tank roof was floating without heat preservation. Simulated conditions were: environment temperatures were 253 K and 233 K, oil temperature was 320 K, and physical properties of crude oil tank are shown in Table 1. Meshing is shown in Figure 2.

Table 1. The basic physical parameters of crude oil

Density ρ [kg/m^3]	Specific heat c [kJ/[kg·K]]	Volume expansion coefficient $\beta \times 10^6$ [1/T]	Kinematic viscosity $v \times 10^{-6}$ m^2/s	Heat conductivity coefficient λ [W/[m·K]]
838.8	1.94	890	17	0.136

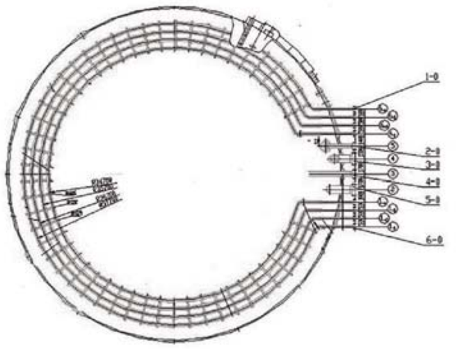

Figure 1. One hundred and fifty thousand state model of the floating roof tank

Figure 2. Finite element meshes of the tank

RESULTS AND DISCUSSION

Temperature Distribution Law of Tank

The temperature of storage tank changed with the passage of change of time, which can be known by different time of the temperature cloud of the oil tank center façade. Figure 3a to Figure 3f present the temperature distributions of cloud under the same environment temperature and temperature change over time. Low temperature zone mainly appeared at the top, side wall and bottom of tank and the center temperature was slightly reduced, finally achieved the core temperature. It was inferred that near the wall of that temperature layer change was transition layer. Due to exothermic process of the oil in storage tank, there was natural internal convection. Figure 4a to Figure 4f shows the velocity distributions of cloud. We can find that high temperature of oil caused natural heat flow to the roof, and relatively low temperature oil was under natural convection around to the tank bottom movement. This

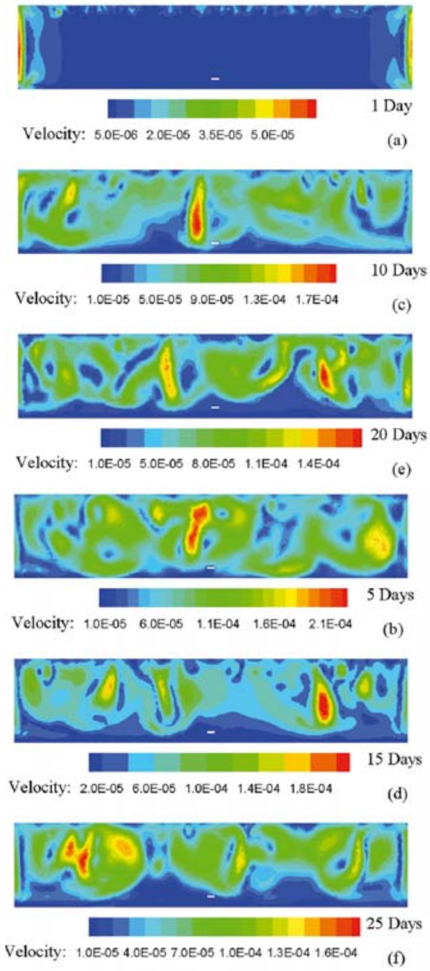

Figure 4. Velocity distribution of storage tank temperature, (a) 1 day, (b) 5 days, (c) 10 days, (d) 15 days, (e) 20 days, (f) 25 days

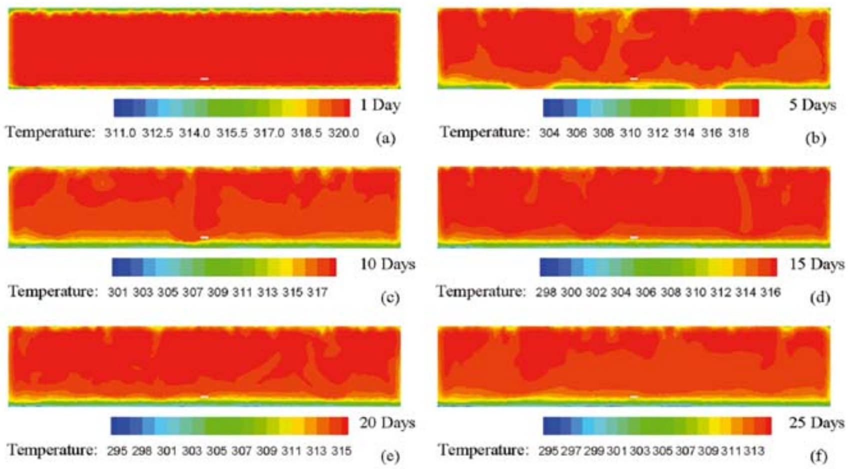

Figure 3. Temperature distribution of storage tank temperature, (a) 1 day, (b) 5 days, (c) 10 days, (d) 15 days, (e) 20 days, (f) 25 days

retained the of relative low temperature oil mostly near the bottom. With the passage of time, oil near the tank bottom had great temperature gradient. As a result of the existence of natural convection, the thickness of transition layer was heterogenous. For low temperature transition layer of roof and thin wall, the transition of tank bottom layer was gradually thickening with the passage of time. The transition layer was thicker at the lower the temperature. The judgment of low temperature area is obtained from the thickness of transition layer.

Radial and Axial Temperature Analysis of Stationary Storage Tank

Take two straight lines in the storage tank, the one is from (0,0,0) to (0,0,H), which is used to display the axial temperature; the other one is from (–L,0,H/2) to (L,0,H/2),which is used to display the radial temperature, the H is liquid level height, L is tank radius. Figure 5 and Fig. 6 are graphs of variation over time of axial temperature curve for the tank and the radial temperature curve.

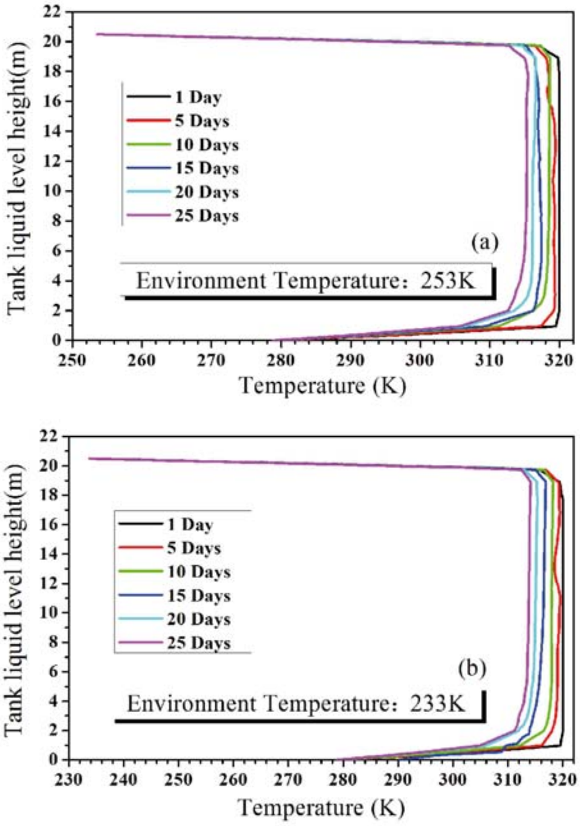

Figure 5. Storage tank with axial temperature change curve over time, (a) environment temperature 253 K and (b) environment temperature 233 K

When the ambient temperatures are 253 K and 233 K respectively, we can find the roof, the distribution of tank bottom and tank center temperature from the axial temperature distribution curve. At the same time under the condition of different environmental temperature, thickness of roof and bottom temperature transition region basically remain unchanged, the temperature of the roof of the transition layer thickness is small, and the thickness of which is about 1.2 m. This is due to the form of heat transfer is mainly natural convection, heat oil to the roof movement, at the same time cold oil to the tank bottom movement, which caused the temperature of the tank bottom transition layer is thick, and the thickness of which is about 1.8 m.

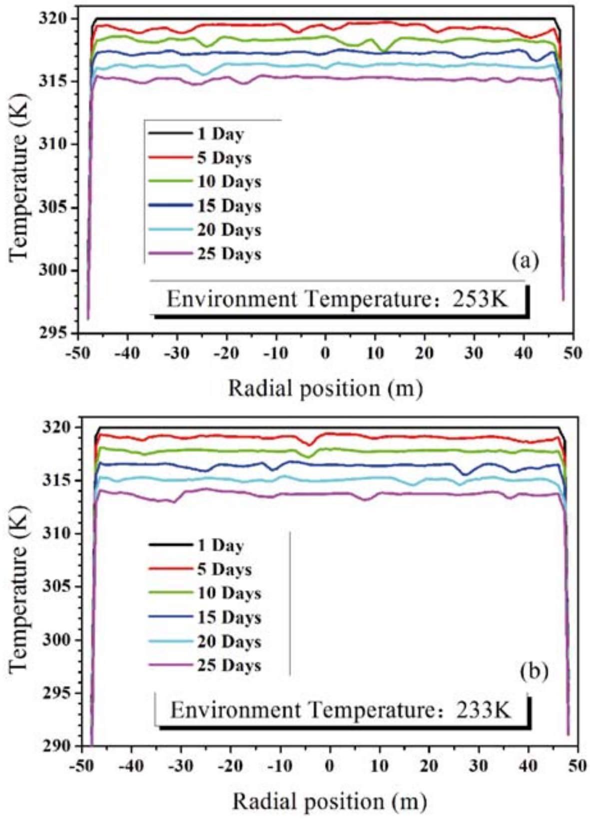

Figure 6. Tank radial temperature change curve over time, (a) environment temperature 253 K and (b) environment temperature 233 K

When the ambient temperature are 253 K and 233 K respectively, we can find the distribution of tank wall and tank center temperature, from the radial temperature distribution curve, at the same time under the condition of different environmental temperature, thickness of wall temperature transition region basically remain unchanged, but the thickness of temperature transition layer near the tank wall is not large, this is due to the tank wall has the thermal insulation layer, relative roof without the conditions of the thermal insulation layer, so the thickness of temperature transition layer near the tank wall should be the smallest, which is about 0.5~0.8m. Because the volume of a storage tank is bigger, oil has a certain thermal motion characteristics under the effect of natural convection, which makes the temperature of the tank inside the same horizontal plane has a certain difference in temperature, thus there are certain fluctuation can be seen on the radial temperature distribution curve.

Center Temperature Analysis of Stationary Storage Tank

When the ambient temperatures are 253 K and 233 K respectively, tank center temperature changing with time curve as shown in Figure 7. we can find that temperature is gradually reduce with the change of time by the figure, and the temperature drop rate is gradually reduce, which is mainly due to the changes over time, temperature difference of oil temperature and environmental temperature is gradually decreased, in addition, with the change of time, on the tank wall solidified oil layer

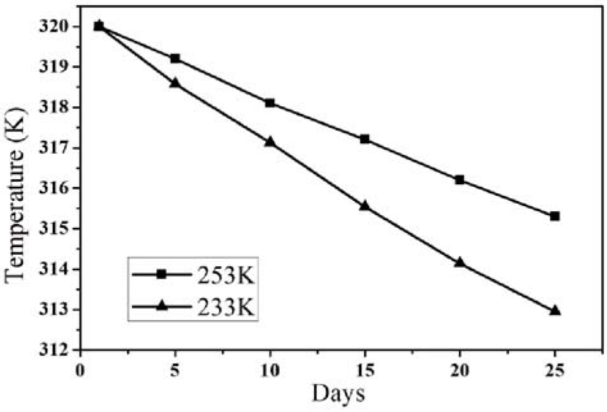

Figure 7. Tank center temperature change curve over time

thickening, which hinders the heat exchange between oil within the tank and the environment, The impaction of condensate reservoir for oil tank is the effect of the thermal insulation layer, these two factors above, which makes oil within the tank with the increase of time and temperature lowering speed gradually slow down.

The center temperature distribution curve for simulation working conditions, it can be seen that the initial temperature of the oil is 320 K, the center of the oil temperature with the passage of time is gradually reduced, when the environment temperature is 253 K, the center of the oil temperature decrease about 5 K respectively within 25 days; when the environment temperature is 233 K, the center of the oil temperature decrease about 7 K respectively within 25 days.

COMPARISON BETWEEN NUMERICAL AND MEASURED RESULTS

In order to the accuracy of the storage tank temperature field calculation results for validation, we compared it with the measured data. Temperature test data are from VITO MTT temperature measuring system 150000 square tank. The system is installed on the tank guide column and is consists of 14 temperature measuring points, respectively, which monitors the oil temperature from 2.7 m to 20.7 m at the tank bottom, the layout of its temperature measurement points are listed in Table 2, Figure 8 for temperature measurement system schematic diagram, he system of temperature measuring element uses PT100 platinum resistance, temperature measurement accuracy is ≤±0.1 K, measurement resolution is 0.01 K.The temperature measuring system not only the average temperature can be output but also output temperature distribution, completely accords with the mainstream of almost all standard, for example, API,ISO,OIML,NMI and so on, radar level gauge, which is connected with temperature measurement system, putting the temperature signals to the computer terminal, and there is a special software for data acquisition.

Table 2. Tank temperature measuring point distribution

Number	Location [m]	Number	Location [m]
1	2.7	2	4.08
3	5.47	4	6.85
5	8.24	6	9.62
7	11.01	8	12.39
9	13.78	10	15.16
11	16.55	12	17.93
13	19.32	14	20.7

Note: the temperature measuring point location for the distance from the tank bottom.

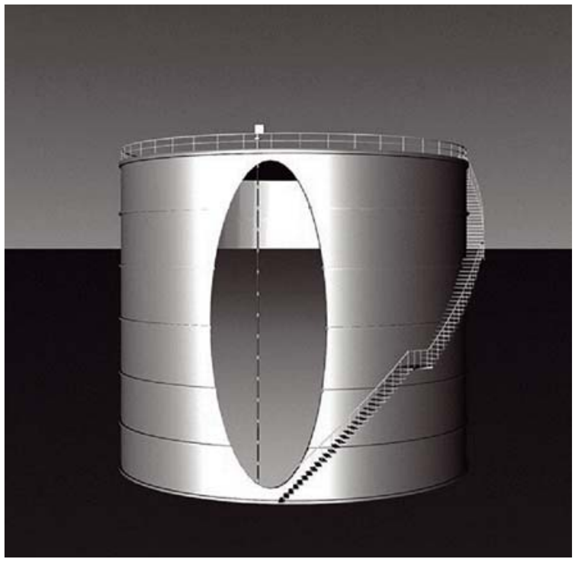

Figure 8. Temperature measuring device

Because winter storage tank has been in a process of temperature maintenance, which can't reflect real resting oil storage tank without heat source heating temperature change, we get the actual data according to the summer without heat source, and be contrast of simulate the temperature distribution of the temperature of the measured points with radar, and process of simulation method is correct, if summer contrast in the range of allowable error, we can get that the simulation method in the storage tank is feasible in running in winter.

According to the measured data of storage tank from May 1, 2015 (Table 3) to May 2, 2015 (Table 4), liquid level height is 8.5 meters, in view of the low level of analysis and comparison between the numerical simulation and the measured temperature, we can get the relative error is within 5%. The details about simulation and measured are displayed in Figure 9 a and Figure 9 b.

According to the measured data of storage tank from June 26, 2015 (Table 5) to June 27, 2015 (Table 6), liquid level height is 14.3 meters, in view of the low level of analysis and comparison between the numerical simulation and the measured temperature, we can get the relative error is within 5%. The details about simulation and measured are displayed in Figure 10a and Figure 10b.

Table 3. The calculation results compared with the measured results (May 1, 2015)

Date	Tank level [m]	Serial number of measuring points	Measured values [K]	Calculated value [K]	Absolute error [K]	Relative error [%]
2015-5-1	8.5	1 [2.7 m]	314.35	314.296	0.054	0.13
2015-5-1	8.5	2 [4.08 m]	314.58	314.454	0.126	0.30
2015-5-1	8.5	3 [5.47 m]	314.59	314.503	0.087	0.21
2015-5-1	8.5	4 [6.85]	314.42	314.353	0.067	0.16
2015-5-1	8.5	5 [8.24]	296.85	297.763	0.931	3.83

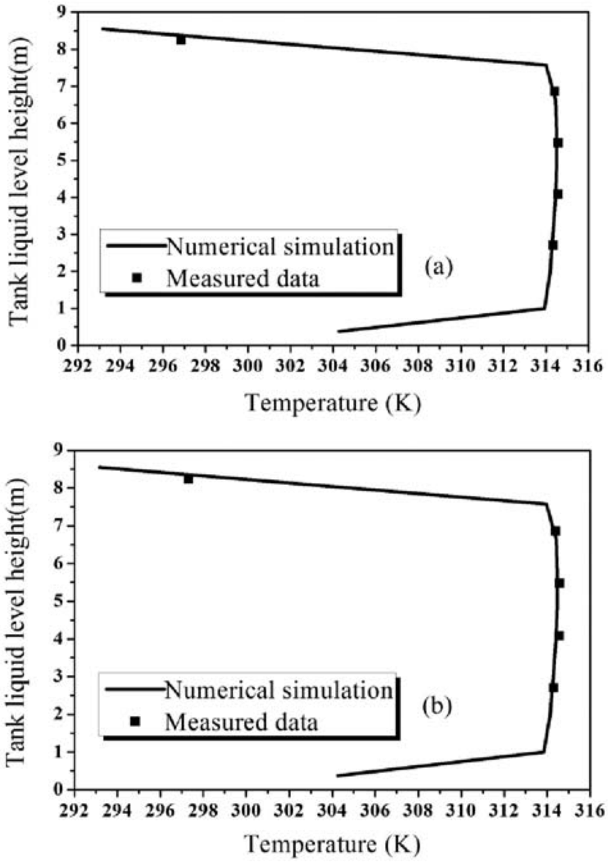

Figure 9. Level 8.5 meters simulation compared with the measured, (a) May 1, 2015 and (b) May 2, 2015

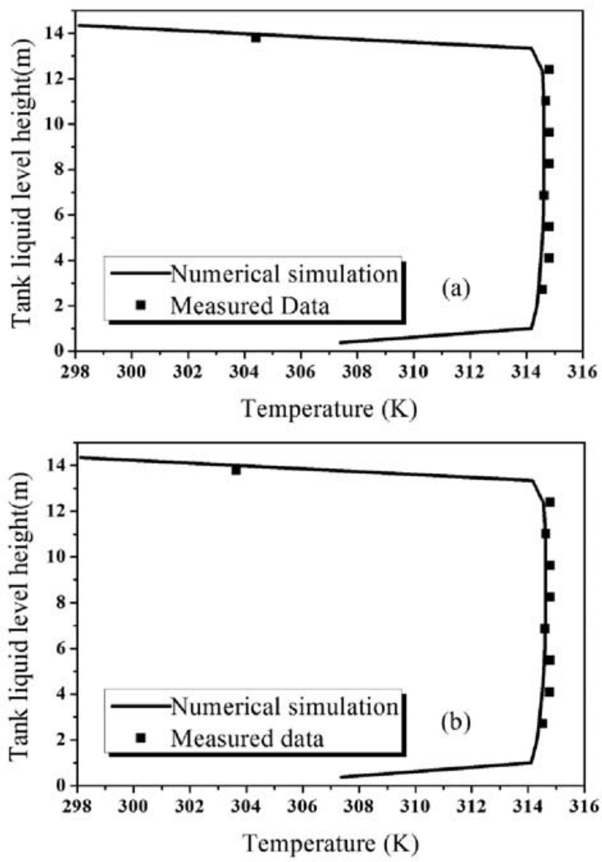

Figure 10. Level 14.3 meters simulation compared with the measured, (a) June 26,2015 and (b) June 27,2015

Table 4. The calculation results compared with the measured results (May 2, 2015)

Date	Tank level [m]	Serial number of measuring points	Measured values [K]	Calculated value [K]	Absolute error [K]	Relative error [%]
2015-5-2	8.5	1 [2.7 m]	314.32	314.234	0.086	0.21
2015-5-2	8.5	2 [4.08 m]	314.56	314.412	0.148	0.36
2015-5-2	8.5	3 [5.47 m]	314.58	314.475	0.105	0.25
2015-5-2	8.5	4 [6.85]	314.40	314.324	0.076	0.18
2015-5-2	8.5	5 [8.24]	297.32	297.752	0.432	1.78

Table 5. The calculation results compared with the measured results (June 26, 2015)

Date	Tank level [m]	Serial number of measuring points	Measured values [K]	Calculated value [K]	Absolute error [K]	Relative error [%]
2015-6-26	14.3	1 [2.7 m]	314.57	314.422	0.148	0.36
2015-6-26	14.3	2 [4.08 m]	314.80	314.516	0.248	0.68
2015-6-26	14.3	3 [5.47 m]	314.80	314.578	0.222	0.53
2015-6-26	14.3	4 [6.85 m]	314.63	314.608	0.022	0.05
2015-6-26	14.3	5 [8.24 m]	314.81	314.619	0.191	0.45
2015-6-26	14.3	6 [9.62 m]	314.81	314.620	0.190	0.45
2015-6-26	14.3	7 [11.01 m]	314.69	314.610	0.080	0.19
2015-6-26	14.3	8 [12.39 m]	314.81	314.549	0.261	0.62
2015-6-26	14.3	9 [13.78 m]	304.41	304.291	0.119	0.38

Table 6. The calculation results compared with the measured results (June 27, 2015)

Date	Tank level [m]	Serial number of measuring points	Measured values [K]	Calculated value [K]	Absolute error [K]	Relative error [%]
2015-6-27	14.3	1 [2.7 m]	314.52	314.376	0.144	0.35
2015-6-27	14.3	2 [4.08 m]	314.76	314.491	0.269	0.64
2015-6-27	14.3	3 [5.47 m]	314.78	314.564	0.216	0.52
2015-6-27	14.3	4 [6.85 m]	314.60	314.599	0.001	0
2015-6-27	14.3	5 [8.24 m]	314.78	314.609	0.171	0.41
2015-6-27	14.3	6 [9.62 m]	314.78	314.609	0.171	0.41
2015-6-27	14.3	7 [11.01 m]	314.63	314.595	0.035	0.08
2015-6-27	14.3	8 [12.39 m]	314.79	314.529	0.261	0.62
2015-6-27	14.3	9 [13.78 m]	303.65	304.272	0.622	2.03

CONCLUSION

Based on the variable physical model, a mathematical model of heat transfer and flow of oil in a large floating roof crude oil storage tank was established. The finite element method is utilized to solve the model discretely. Through the study of the numerical simulation of large floating roof tank, we can get temperature field distribution of the results of crude oil in a large floating roof tank. The variation law of the temperature field and the velocity field with time in the unsteady heat transfer process of crude oil in the storage tank was analyzed. When the tank remains unchanged, the temperature of the roof of the transition layer thickness is static, low temperature zone mainly appeared at the top. Side wall and bottom of tank, near the center temperature was slightly lower. Thickness of roof and bottom temperature transition region basically small, the thickness of which was about 1.2 m, the thickness of temperature transition layer near the tank wall was the smallest (about 0.5–0.8 m). The influence of ambient temperature on the temperature field of crude oil in the tank was analyzed. The simulation results matched with the experimental results having error lower than 3.8%. It is demonstrated that the model is better and the mathematical model is reasonable.

Conflict of interest

None declared.

LITERATURE CITED

1. Wei, S. & Qinglin, C. et al. (2016). Research on the variation law of heating temperature field and the effective energy utilization rate of a steam coil for the floating roof tank. Numerical Heat Trans. 70, 1345–1355.

2. Nurten, V. (2003). Numerical analysis of the transient turbulent flow in a fuel oil storage tank. Int. J. Therm. Sci. 46, 3429–3440. DOI: 10.1016/S0017-9310(03)00145-5.

3. Wang, M., Zhang, X. & Yu, G. et al. (2017). Numerical study on the temperature drop characteristics of waxy crude oil in a double-plate floating roof oil tank. Appl. Therm. Enginee. 124, 560–570.

4. Oliveski, R.D.C., Macagnan, M.H., Copetti, J.B. & Petroll, A.D.L. (2005). Natural convection in a tank of oil: experimental validation of a numerical code with prescribed boundary condition. Exp. Therm. Fluid Sci. 29, 671–680. DOI: 10.1016/j.expthermflusci.2004.10.003.

5. Oliveski, R.D.C., Krenzinger, A. & Vielmo, H.A. (2001). Experimental and numerical analysis of a thermal storage tank. Exp. Therm. Fluid Sci. 3, 2193–2198. DOI: 10.1002/er.1057.

6. Oliveski, R.D.C., Krenzinger, A. & Vielmo, H.A. (2003). Cooling of cylindrical vertical tanks submitted to natural internal convection. Int. J. Therm. Sci. 46, 2015–2026. DOI: 10.1016/S0017-9310(02)00508-2.

7. Rejane De Cesaro Oliveski. (2013). Correlation for the cooling process of vertical storage tanks under natural convection for high Prandtl number. Int. J. Heat Mass Trans. 57, 292–298.

8. Lin, W.X. & Armfield, S.W. (1999). Direct simulation of natural convection cooling in a vertical circular cylinder. Int. J. Therm. Sci. 42, 4117–4130. DOI: 10.1016/S0017-9310(99)00074-5.

9. Atmane, M.A., Chan, V.S.S. & Murray, D.B. (2003). Natural convection around a horizontal heated cylinder: the effects of vertical confinement. Int. J. Heat Mass Trans. 46, 3661–3672. DOI: 10.1016/S0017-9310(03)00154-6.

10. Sanapala, V.S., Velusamy, K. & Patnaik, B.S.V. (2016). CFD simulations on the dynamics of liquid sloshing and its control in a storage tank for spent fuel applications. Ann. Nuc. Energy 94, 494–509.

11. Oliveira, P.J.R. & Issa, R.I. (2001). An improved PISO algorithem for the computation of buoyant driven flows. Num. Heat Trans. B-Fund. 40, 473–493.

12. González, I., Pérez-Segarra, C.D., Lehmkuhl, O., Torras, S. & Oliva, A. (2016). Thermo-mechanical parametric analysis of packed-bed thermocline energy storage tanks. Appl. Energy 179, 1106–1122.

13. Rodriguez, I., Castro, J., Perez-Segarra, C.D. & Oliva, A. (2009). Unsteady numerical simulation of the cooling process of vertical storage tanks under laminar natural convection. Int. J. Therm. Sci. 48, 708–721. DOI: 10.1016/j.ijthermalsci.2008.06.002.

14. Fernandez-Seara, J., Francisco, U., Dopazo, J. & Alberto, J. (2011). Experimental transient natural convection heat transfer from a vertical cylindrical tank. Appl. Therm. Eng. 31, 1915–1922. DOI: 10.1016/j.applthermaleng.2011.02.037.

15. Stig, G. & Jensen, A. (2012). Natural convection heat transfer from two horizontal cylinders at high Rayleigh numbers. Int. J. Heat Mass Trans. 55, 5552–5564. DOI: 10.1016/j.ijheatmasstransfer.2012.05.033.

16. Stig, G., Atle, J.B. & Anders, P.R. (2011). PIV investigation of buoyant plume from natural convection heat transfer above a horizontal heated cylinder. Int. J. Heat Mass Trans. 54, 4975–4987. DOI: 10.1016/j.ijheatmasstransfer.2011.07.011.

17. Reymond, O., Murray, D.B. & O'Donovan, T.S. (2008). Natural convection heat transfer from two horizontal cylinders. Exp. Therm. Fluid Sci. 32, 1702–1709. DOI: 10.1007/978-3-319-08132-8_2.

18. Persoons, T., O'Gorman, I.M., Donoghue, D.B., Byrne, G. & Murray, D.B. (2011). Natural convection heat transfer and fluid dynamics for a pair of vertically alifned isothermal horizontal cylinders. Int. J. Therm. Sci. 54, 5163–5172. DOI: 10.1016/j.ijheatmasstransfer.2011.08.033.

19. Mawire, A. (2013). Experimental and simulated thermal stratification evaluation of an oil storage tank subjected to heat losses during charging. Appl. Energy 108, 459–465.

20. Yu, D. (2005). Development on temperature monitoring system of large floating roof tank. Oil Gas Stor. Transport 24, 41–43.

21. Yu, D. & Fang, X.Y. (2003). Temperature drop characteristics of oil in the large breathing roof tank. Oil Gas Stor. Transport 22, 47–49.

22. Li, W., Wang, Q., Li, R., Li, C., Yu, B., Zhang, J. & Dai, P. (2011). Numerical study on temperature field of a large floating roof oil tank. J. Chem. Indus. Eng. 62, 108–112.

23. Chouikh, R., Guizani, A., Cafsi, A. El, Maalej, M. & Belghith, A. (2000). Experimental study of the natural convection flow around an array of heated horizontal cylinders. Renew. Energ. 21, 65–78. DOI: 10.1016/S0960-1481(99)00120-2.

24. Bin Zhao, (2012). Numerical simulation for the temperature changing rule of the crude oil in a storage tank based on the wavelet finite element method. J. Therm. Anal. Calorim. 107, 3, 87–393.

25. Tao, W. (2001). Numerical heat transfer. Xi 'an: Xi 'an Jiaotong University Press.

26. Jian, Z., Dong, H., Wei, L.X. & Liu, Y. (2015). Heat Loss Test and Estimate for the Large-scale Floating Roof Tank. Open Petrol. Eng. J. 8, 117–125. DOI: 10.2174/1874834101508010117.

27. Suhas, P. (1980). Numerical Heat Transfer and Fluid Flow. Boca Raton: CRC Press.

28. Versteeg, H.K. & Malalasekera, W. (2007). An Introduction to Computational Fluid Dynamics: The Finite Volume Method. (2nd ed). New York: Pearson.

29. Jian Z., Liu, Y., Wei, L.X. & Dong, H. (2014). Transient Cooling of Waxy Crude Oil in a Floating Roof Tank. J. Appl. Mat. 2014, 1–12. DOI: 10.1155/2014/482026.

30. Cheng, Q.L., Sun, W., Shao, S., Li, Z. & Yi, X. (2014). The study of variation law and influence factors of heat transfer coefficient for floating roof storage tank. Energ. Conserv. Technol. 32, 151–154.

31. Fan, J.W. & Liu-et, Y. al. (2017). Hydrodynamics of residual oil droplet displaced by polymer solution in microchannels of lipophilic rocks. Int. J. Heat Technol. 35, 611–618.

32. Rahimi, M. & Parvareh, A. (2007). CFD study on mixing by coupled jet-impeller mixers in a large crude oil storage tank. Compu. & Chem. Enginee. 31, 737–744.