27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

COB-2023-2352
TRANSIENT THERMAL ANALYSIS OF THERMOPLASTIC COMPOSITES PIPELINES FOR OIL-GAS MULTI-PHASE FLOW WITH ELECTRIC HEAT TECHNOLOGY

Jinhong Yu
College of Safety and Ocean Engineering, China University of Petroleum-Beijing 18 Fuxue Road, Beijing, 102249, China
Nuclear Engineering Program, COPPE, Federal University of Rio de Janeiro CP 68509, Rio de Janeiro, 21941-972, Brazil

Jian Su
Nuclear Engineering Program, COPPE, Federal University of Rio de Janeiro CP 68509, Rio de Janeiro, 21941-972, Brazil
sujian@nuclear.ufrj.br

Chen An
College of Safety and Ocean Engineering, China University of Petroleum-Beijing 18 Fuxue Road, Beijing, 102249, China
anchen@cup.edu.cn

Abstract. *This paper presents an symmetric mathematical model for the transient heat transfer for thermoplastic composites pipelines with electric heat technology. A lumped parameter method was employed to solve differential equations and predict the average temperature of the fluid in thermoplastic pipelines. In addition, the study also investigated the influence of different heating power, heating time and flow rates on the temperature distribution of the produced fluid in pipeline under normal start-up and shutdown conditions. The results showed that the fluid temperature raised with the increase of heating power under the same heating time. The temperature of the fluid in the pipeline showed a downward trend along the length direction, and then gradually paralleled to the temperature drop curve with the enlarge of the distance. The larger the flow rate, the corresponding time required to reach the steady state temperature was also greatly shortened. Finally, we also proposed segmented heating method that minimises the power requirement for a given minimum temperature of the fluid, which has a significant effect in reducing power and saving energy. Overall, the lumped model demonstrated its effectiveness in predicting temperature variation in thermoplastic composite pipelines during the transportation of oil and gas media.*

Keywords: *Thermoplastic composites pipelines; Transient heat conduction; Lumped model; Multi-layer structure; Electrical heating method.*

1. INTRODUCTION

Thermoplastic Composite Pipe (TCP) is made of reinforced thermoplastic composite material, laminated from thermoplastic resin and reinforcing fibers. TCP is lightweight, corrosion resistant, has a high strength to weight ratio and is highly resistant to chemical attack and abrasion characteristics. Therefore, TCP generally has better strength and stiffness properties and can provide several advantages over traditional steel and FRP pipes. For these reasons, TCP is often used in a wide variety of applications including oil and gas production, deep sea drilling, wand industrial piping systems.

TCP can be used in conjunction with heating cables or elements in some applications such as cold climates or fluid transfer systems. The heating cable was usually located between the middle layer and the outer protective layer, which generates energy through electric heating and provides heat for the fluid to maintain the fluidity (Sunday *et al.*, 2021). Generally speaking, the layout of the heating cable should ensure that the medium in the pipeline can be heated quickly and evenly to prevent the fluid from freezing or solidifying during transportation (Su *et al.*, 2012). One arrangement of the heating cable is to embed the heating cable into the pipe during manufacture to form an integrated structure with the pipe, ensuring it not only withstand the the mechanical loading and the thermodynamic requirements (Davies *et al.*, 2005), but also prevent the heating cables from being damaged by external objects or contact in order to improve the transmission efficiency and stability of the pipeline (Barbosa *et al.*, 2019; Wilkins, 2018).

Research on offshore TCP are focus on the overall pipeline and studies the dynamic response of thermoplastic pipelines under external environmental loads (Hastie *et al.*, 2022), such as Evgeny V. Morozov et al. (Morozov and Yu, 2016). Much work has also been done on transient heat transfer of multi-layered composite structures. For example, De Monte (De Monte, 2002), Bautista (Bautista *et al.*, 2005), and Sadat (Sadat, 2006) mainly studied the transient heat conduction and heat convection in one-dimensional multilayer composite structures. Lu *et al.* (2005, 2006a,b) combined the Laplace transform and the Separation of variables methods to determine the temperature distribution in 2D rectangular and cylindrical media. The analytical solutions in the cylindrical coordinate system were restricted to the r-z coordinates (Lu *et al.*, 2006a,b). In terms of solving the transient conduction and convection of multi-layer composite structures such as flat plates, pipes, and cooling heat transfer, some solving methods have also been developed. The typical methods are the lumped parameter method (Viot *et al.*, 2018; An and Su, 2013; Su *et al.*, 2009; Tan *et al.*, 2009), the Laplace transform method (Li and Lai, 2013), separation of variables method (Bechiri and Mansouri, 2016), the finite integral transform technique (Crepeau and Siahpush, 2012) and finite difference method (Sundén, 1986). However, these studies are basically carried out for symmetric problems. For asymmetric problems, Singh et al. (Singh and Jain, 2008) and Jain et al. (Jain and Singh, 2009) proposed a closed form analytical double-series solution for the multidimensional unsteady heat conduction problem in polar coordinates with multiple layers in the radial direction. As an extension of the previous work, Jain et al. (Jain and Singh, 2010) presented an analytical series solution for transient boundary-value problem of heat conduction in r-θ spherical coordinates, which is applicable in spherical or part-spherical multi-layer geometries.

This paper presents improved lumped models for analyzing the transient heat transfer characteristics combined convective and conduction in multi-layer thermoplastic composite pipe with electric heating cables based on Hermite approximations. The governing partial differential equations are solved numerically by finite difference methods. Firstly, the temperature prediction model for multi-layer composite pipes was derived. Secondly, the theoretical model predicted the fluid temperature and the temperature distribution of each layer in thermoplastic composite pipes under the heating, start-up conditions, as well as discussed the influence of different heating power, heating time and flow rates on the temperature distribution.

2. PROBLEM DESCRIPTION

The mathematical model established in this paper is shown in the Fig. 1. It is a multi-layer composite pipeline composed by four concentric circles. From the inner layer to the outer layer, there are oil medium, inner lining layer, electrical heating layer, fiber reinforced layer and outer protective layer respectively. The inner lining layer, fiber reinforcement layer and outer protective layer are mainly composed of APC-2PEEK, AS4/APC-2 fiber, and APC-2PEEK. The fluid parameters and materials parameters for each layer of the pipeline are shown in Table 1. It is assumed that the pipeline with a length of 15km and an inner diameter of 0.076m, the inlet and outlet temperature of the fluid are taken as 70°C and 12.57°C, the average flow velocity of fluid is 0.5 m/s with a mass flow rate of 8.18 kg/s and the environment temperature is given as 4 °C. The overall heat transfer coefficient of the pipeline is 4.82 W/(m^2·°C). We also obtained h_1 and h_0 are 181.65 W/(m^2·°C) and 200 W/(m^2·°C), ΔT_m is 42.94°C.

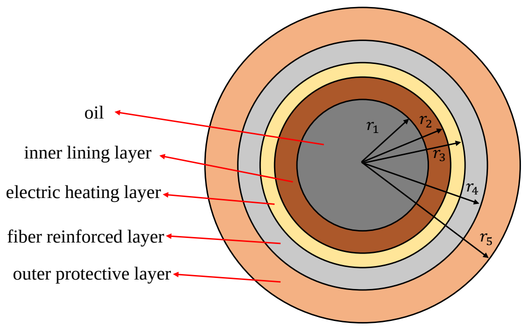


Figure 1. Sketch of the multilayered thermoplastic composite pipeline with heating cables.

2.1 Energy Equation for Fluid

For this multi-layer thermoplastic composite pipeline, the fluid medium transported is fully developed in the pipeline, and the contact between the fluid and the inner wall of the pipeline is a convective heat transfer condition on the cross-section. Assuming that the average velocity of the fluid is V_f, the fluid in the pipeline satisfied the one-dimensional transient energy equation, which can be written as:

$$\rho_f c_{pf} \frac{\partial T_f(z,t)}{\partial t} + \rho_f c_{pf} V_f \frac{\partial T_f(z,t)}{\partial z} = -\frac{2h_1 \pi r_1}{A}(T_f(z,t) - T_1(r_1,z,t)), \text{ for } 0 \le z < L \text{ and } t > 0, \tag{1}$$

where, $T_f(z,t)$ is the temperature of the fluid, $T_1(r_1,z,t)$ is the temperature of the inner wall at the first layer for pipeline, ρ_f is the density of the produced fluid, c_{pf} is the specific heat, and A is the cross-section area of the flow passage.

Table 1. Pipe geometric parameters and materials thermodynamic Parameters.

Parameter	$j=1$	$j=2$	$j=3$	$j=4$	$j=5$
r_j/m	0.076	0.084	0.100	0.180	0.188
ρ_j/(kg/m^3)	901.27(ρ_f)	1300	1000	1600	1300
c_{pj}/J/(kg·°C)	2070(c_{pf})	1069	1000	855	1069
k_j/W/(m·°C)	0.1308(k_f)	0.242	0.26	0.43	0.242

2.2 Transient Heat Conduction for Composite Pipe

The heat transfer in multi composite layers carried out the form of heat conduction, assuming that each layer is homogeneous and isotropic with no phase transition. The heating system is basically composed of heating cables distributed around the pipeline, neglecting the heat conduction in longitudinal and circumferential directions. The one-dimensional transient heat conduction equations for multi-layer thermoplastic pipe can be written as follows:

$$\rho_j c_{pj}\frac{\partial T_j(r,z,t)}{\partial t} = k_j\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial T_j(r,z,t)}{\partial r})+g_j(r,z,t),\ \text{for } r_j < r < r_{j+1},\ 0<z<L,\ j=1,2,3,4 \text{ and } t>0, \quad (2)$$

where, $T_j(r,z,t)$ is the temperature at time t when the axial coordinate of the j-th layer pipeline is z, k_j is the thermal conductivity, $g_j(r,z,t)$ is heat generation rate per unit volume.

Furthermore, the heat transfer between solid and fluid is convective heat exchange. Therefore, the boundary conditions are satisfied between the fluid and the inner wall of the pipe, the outer wall of the pipe and external environment are respectively expressed as:

$$-k_1\frac{\partial T_1(r_1,z,t)}{\partial r} = h_1(T_f(z,t)-T_1(r_1,z,t)),\ \text{for } r=r_1,\ 0<z<L \text{ and } t>0, \quad (3)$$

$$-k_4\frac{\partial T_4(r_5,z,t)}{\partial r} = h_o(T_4(r_5,z,t)-T_a),\ \text{for } r=r_{j+1},\ j=4 \text{ and } t>0, \quad (4)$$

$$T_j(r,z,t) = T_{j+1}(r,z,t), \text{for } r=r_{j+1},\ j=1,2,3 \text{ and } t>0, \quad (5)$$

$$k_j\frac{\partial T_j(r,z,t)}{\partial r} = k_{j+1}\frac{\partial T_{j+1}(r,z,t)}{\partial r},\ \text{for } r=r_{j+1},\ j=1,2,3, \quad (6)$$

where, h_1 is the heat transfer coefficient between the produced fluid and the innermost layer of the pipeline, and h_0 is the heat transfer coefficient between the outermost layer and the environmental fluid. T_a is the temperature of the surrounding seawater, 4 °C.

The initial conditions are given by

$$T_f(z,t) = T_{f0}(z),\ \text{when } t=0, \quad (7)$$

$$T_f(0,t) = T_{f,in},\ \text{when } z=0, \quad (8)$$

$$T_j(r,z,t) = T_{j0}(r,z),\ \text{when } t=0, \quad (9)$$

$$T_j(r,0,t) = T_{fin},\ \text{at } r_j<r<r_{j+1}, \text{and } z=0, \quad (10)$$

where, T_{fin} is the fluid inlet temperature.

3. SOLUTION METHODOLOGY

3.1 Lumped Parameters Models

Introduce the spatially average temperatures as follows:

$$T_{avj}(z,t) = \frac{1}{(r_{j+1}^2-r_j^2)}\int_{r_j}^{r_{j+1}} 2rT_j(r,z,t)dr,\ j=1,2,3,4, \quad (11)$$

The plain trapezoidal rule ($H_{0,0}$ approximation) used in averaged temperature and heat flux for each layer can be written as follows:

$$T_{av,j}(z,t) = \frac{r_j}{r_{j+1}+r_j}T_j(r,z,t)|_{r=r_j} + \frac{r_{j+1}}{r_{j+1}+r_j}T_j(r,z,t)|_{r=r_{j+1}},\ j=1,2,3,4, \quad (12)$$

$$T_j(r,z,t)\Big|_{r=r_{j+1}} - T_j(r,z,t)\Big|_{r=r_j} = \frac{r_{j+1}-r_j}{2}\left(\frac{\partial T_j(r,z,t)}{\partial r}\Big|_{r=r_j} + \frac{\partial T_j(r,z,t)}{\partial r}\Big|_{r=r_{j+1}}\right), j=1,2,3,4, \quad (13)$$

The corrected plain trapezoidal rule ($H_{1,1}$ approximation) used in averaged temperature can be written as follows:

$$\begin{aligned} T_{av,j}(z,t) &= \frac{r_{j+1}+5r_j}{6(r_{j+1}+r_j)}T_j(r,z,t)|_{r=r_j} + \frac{5r_{j+1}+r_j}{6(r_{j+1}+r_j)}T_j(r,z,t)|_{r=r_{j+1}} \\ &+ \frac{r_j(r_{j+1}-r_j)}{6(r_{j+1}+r_j)}\frac{\partial T_j(r,z,t)}{\partial r}|_{r=r_j} - \frac{r_{j+1}(r_{j+1}-r_j)}{6(r_{j+1}+r_j)}\frac{\partial T_j(r,z,t)}{\partial r}|_{r=r_{j+1}},\ j=1,2,3,4, \end{aligned} \quad (14)$$

Integrating Equation (4) using the average temperature definition Equation (11), we get

$$\frac{\partial T_{avj}(z,t)}{\partial t} = \frac{2k_j}{(r_{j+1}^2-r_j^2)\rho_j c_{pj}}(r_{j+1}\frac{\partial T_j(r,z,t)}{\partial r}|_{r=r_{j+1}} - r_j\frac{\partial T_j(r,z,t)}{\partial r}|_{r=r_j}) + \frac{g_j(z,t)}{\rho_j c_{pj}},\ j=1,2,3,4, \quad (15)$$

where, the volumetric heat generation rate is independent of the radial coordinate, $g_j(r,z,t) = g_j(z,t)$.

3.2 Finite Difference Solution

The energy equation (1) of the fluid can be discretized in the following form:

$$\rho_f c_{pf}\frac{\mathrm{d}T_f^m(t)}{\mathrm{d}t} + \rho_f c_{pf}V_f\frac{T_f^m(t)-T_f^{m-1}(t)}{\Delta z} = \frac{2h_1\pi r_1}{A_f}(T_1(r_1,z_j,t)|_{r=r_1} - T_f^m(t)),\ m=1,2,...,Nz \quad (16)$$

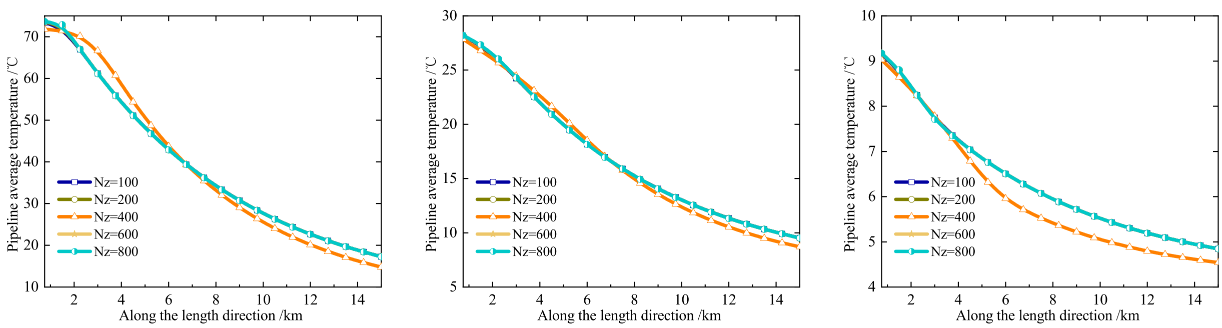
The finite difference method was used to solve the lumped parameter model for the transient temperature problem. The discretization was carried out in axial z direction:

$$\begin{gathered} z_m = m\cdot\Delta z, T_f(z_m,t) = {T_{ffd}}^m(t), T_{av,j}(z_m,t) = {T_{avfd,j}}^m(t), g_j(z_m,t) = {g_{fd,j}}^m(t), \\ \frac{\partial T_{av,j}(z,t)}{\partial t} = \frac{\partial {T_{avfd,j}}^m(t)}{\partial t}, \frac{\partial T_f(z_m,t)}{\partial t} = \frac{\partial {T_{ffd,j}}^m(t)}{\partial t}, \frac{\partial T_f(z,t)}{\partial z} = \frac{{T_{ffd}}^m(t) - {T_{ffd}}^{m-1}(t)}{\Delta z}, \end{gathered} \quad (17)$$

where m=1, 2, . . . , Nz is the total number of axial discrete points.

The mathematical model consists of $5Nz$ ordinary differential equations about time. At each discrete point z_m, there are 4 average temperature equations $T_{av,j}^m(t)$ of the multi-layer pipeline and 1 internal fluid temperature equation $T_f^m(t)$.

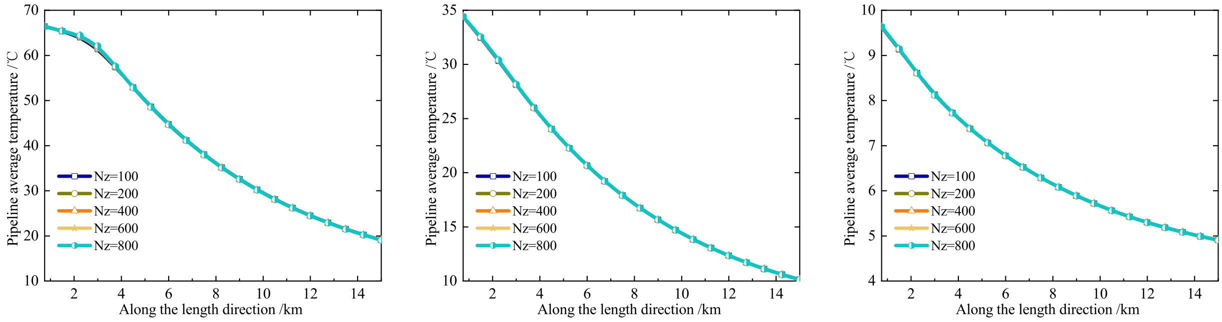
3.3 Numerical Verification



(a) n=1 (b) n=3 (c) n=4

Figure 2. Temperature distribution of the pipeline calculated by $H_{0,0}$ lumped parameter model

Table 2 presents the convergence behavior of the average temperature of the fluid T_f calculated by $H_{0,0}$ lumped models and $H_{1,1}$ improved lumped models with the number of grid points (Nz=100, 200, 400, 600 and 800) at different positions along the length direction of pipelines under different heating time. The average temperature of the fluid corresponding to the two models showed the same changing trend under different grid numbers and different heating times. For certain grid number points, the temperature of the fluid in pipeline minimizes along the length direction with heating time increasing. The temperature of the fluid at the same position in pipeline enhances with the accumulation of the heating time, which is hardly affected by the number of grid points. The results calculated by the improved lumped parameter model varied slightly with the number of grids and showed higher accuracy, as well as the convergence is basically achieved for the number of grids 600. Figure 2 and 3 show the temperature distribution of the inner lining layer, fiber reinforcement



(a) n=1 (b) n=3 (c) n=4

Figure 3. Temperature distribution of the pipeline calculated by $H_{1,1}$ lumped parameter model

layer and outer protection layer along the length direction of the pipeline which is calculated by two lumped parameter models with different grid nodes. It can be seen that the results of the lumped parameter model and the improved lumped parameter model are very close, but the improved lumped parameter model has higher accuracy in temperature prediction, which is reflected in the fact that the result is not sensitive to the variation of the number of grid nodes.

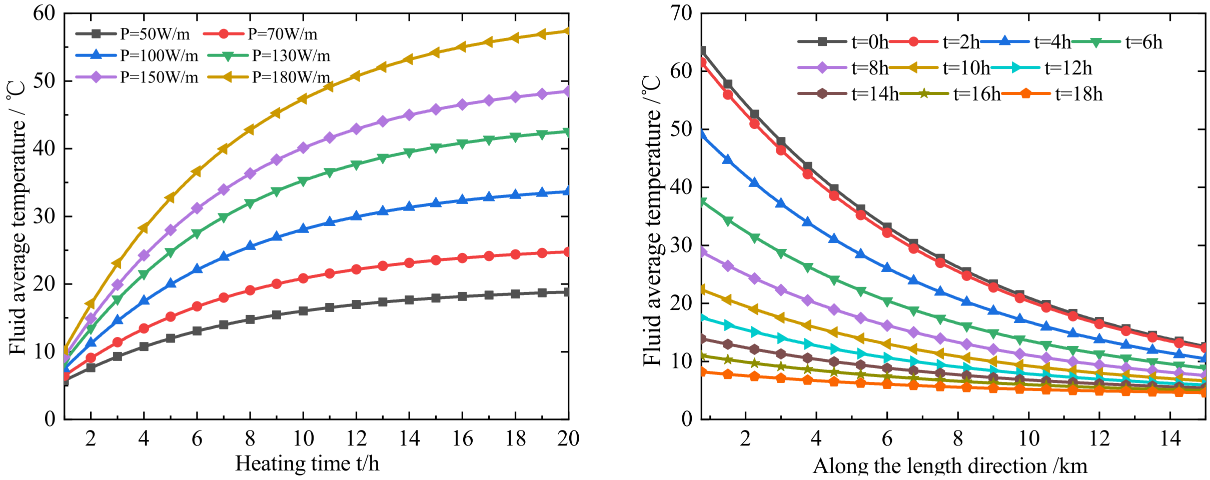
Table 2. Convergence behavior of the average temperature of the fluid calculated by $H_{1,1}/H_{0,0}$ lumped model.

z (km)	Nz = 100	Nz = 200	Nz = 400	Nz = 600	Nz = 800
t = 1h					
3.0	59.8155/62.6334	59.7744/62.5906	59.7496/62.5652	59.7412/62.5566	59.7371/62.5523
6.0	41.7096/43.5636	41.6760/43.5292	41.6593/43.5121	41.6538/43.5064	41.6510/43.5036
9.0	29.6623/30.8756	29.6400/30.8527	29.6289/30.8414	29.6252/30.8376	29.6233/30.8357
12.0	21.6506/22.4378	21.6357/22.4226	21.6283/22.4151	21.6259/22.4126	21.6247/22.4113
15.0	16.3226/16.8265	16.3127/16.8164	16.3078/16.8114	16.3062/16.8097	16.3054/16.8089
t = 2h					
3.0	64.6736/66.7688	65.1241/67.3746	65.4088/67.7702	65.5182/67.9272	65.5763/68.0126
6.0	47.1108/48.8130	47.0418/48.7419	47.0075/48.7065	46.9960/48.6947	46.9903/48.6888
9.0	33.8894/35.0079	33.8434/34.9604	33.8205/34.9368	33.8129/34.9290	33.8091/34.9251
12.0	25.0967/25.8269	25.0661/25.7954	25.0509/25.7797	25.0458/25.7745	25.0433/25.7719
15.0	19.2493/19.7214	19.2290/19.7004	19.2189/19.6900	19.2155/19.6865	19.2138/19.6848
t = 4h					
3.0	58.3479/57.6443	58.2811/57.5392	58.2449/57.4828	58.2325/57.4634	58.2262/57.4537
6.0	50.8545/51.4655	51.1593/51.8506	51.3533/52.1004	51.4279/52.1982	51.4676/52.2507
9.0	38.6661/39.3167	38.5772/39.2257	38.5303/39.1773	38.5146/39.1612	38.5068/39.1531
12.0	29.3183/29.7688	29.2550/29.7037	29.2236/29.6714	29.2131/29.6607	29.2079/29.6553
15.0	23.0974/23.4145	23.0553/23.3712	23.0344/23.3498	23.0275/23.3426	23.0240/23.3391
t = 6h					
3.0	55.2060/54.5708	55.1250/54.4754	55.0837/54.4273	55.0699/54.4111	55.0630/54.4031
6.0	46.8802/46.4732	46.8387/46.4119	46.8137/46.3759	46.8048/46.3631	46.8003/46.3565
9.0	40.2975/40.6386	40.4734/40.8572	40.5869/40.9981	40.6306/41.0527	40.6539/41.0818
12.0	32.0279/32.4157	31.9467/32.3335	31.9003/32.2859	31.8845/32.2696	31.8765/32.2614
15.0	25.6870/25.9805	25.6227/25.9144	25.5908/25.8816	25.5802/25.8708	25.5749/25.8653

4. RESULTS AND DISCUSSIONS

In practice, thermoplastic pipes typically require preheating to reach normal operating temperature before starting up. The purpose of the preheating is to make materials reach the appropriate softness and plasticity with considering a series of factors such as heating power, heat transfer performance, ambient temperature, and heating time so that it can endure pressure and deformation during operation. Reasonable preheating and heating strategies can improve the reliability and safety of pipelines and ensure that pipelines will work at normal operating temperatures.

It can be seen from Fig.4(a) that the greater the heating power, the shorter time required to reach the allowable minimum temperature. When the linear heating power is 100 W/m, 130 W/m, 150 W/m and 180 W/m respectively, the time needed to heat from the ambient temperature to 30°C is about $12h$, $7h$, $6h$ and $4h$. The temperature rising rate is slower under the same heating power, mainly because the temperature difference between the internal medium and the



(a) Preheating conditions (b) Shutdown conditions

Figure 4. Temperature distribution of the produced fluid under different working conditions along the pipeline length.

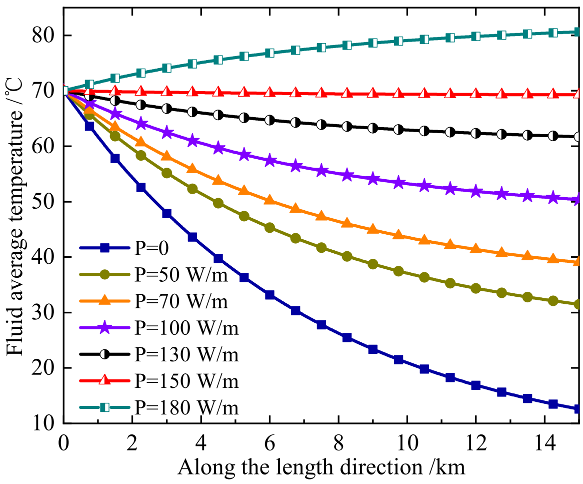
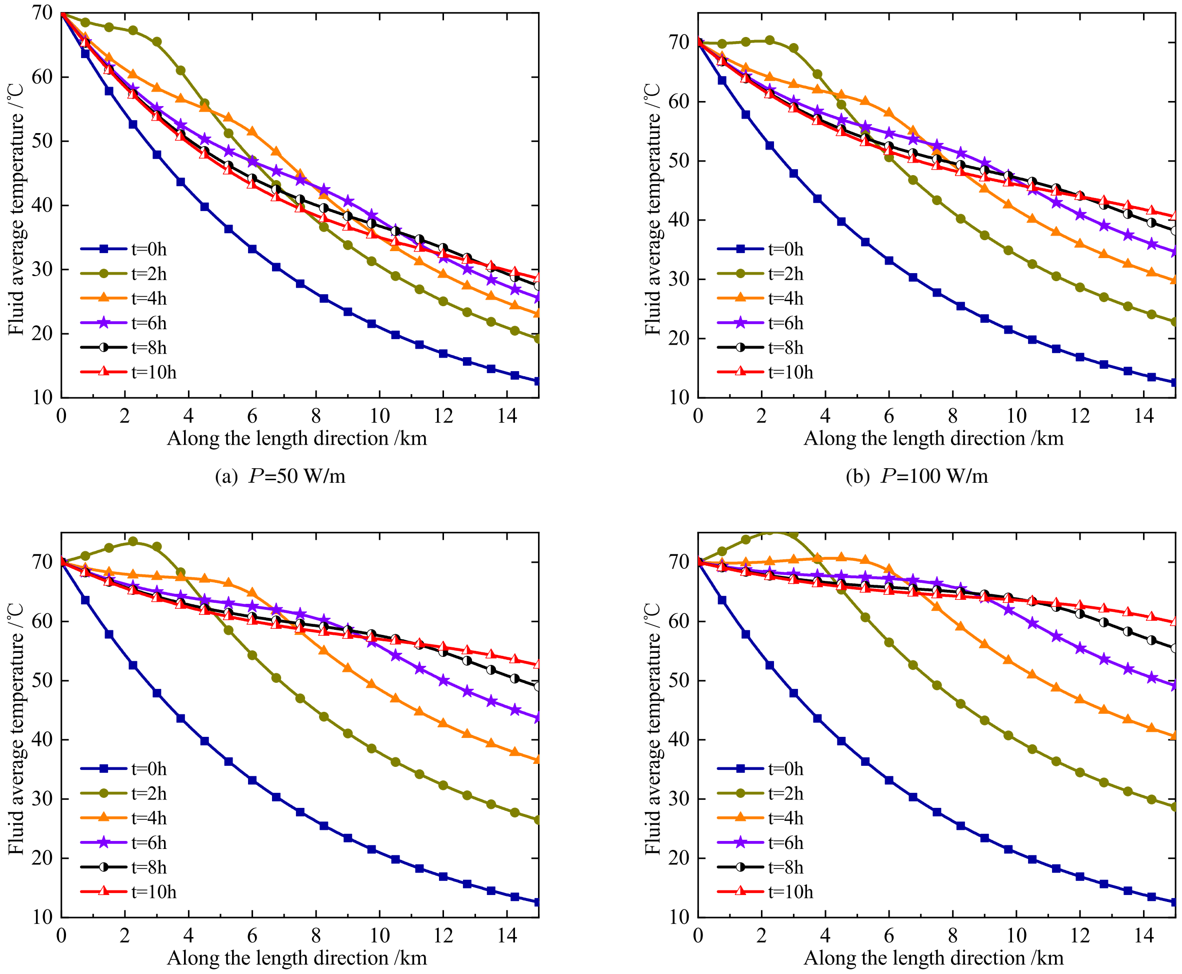


Figure 5. Fluid temperature along the pipeline length under stable-heating condition

environment is getting larger with the accumulation of the heating time, indicating that the oil and gas heat dissipation rate gradually enlarges while the heat provided by the constant heating power is certain. In addition, the heating layer is located between the inner lining layer and the fiber reinforced layer, the heat need to pass through the lining layer before entering into fluid so that the heating power and heating time required to reach the same temperature are longer in principle, indicating that an amount heat have dissipated in this process. It can be seen from Fig.4(b) that the average temperature of the fluid gradually reduces with the extension of the shutdown time, and the temperature drop rate declines with the reduction of the temperature difference between the fluid and the environment. Meanwhile, the safe shutdown time is less than 2 hours if no heating measures are taken at the end of the pipeline, if the temperature of the whole pipeline is below the critical temperature, which verified the necessity of DEH technology under shutdown conditions. For oil pipelines used in deep-sea and polar complex marine environments, the shutdown time to maintenance is generally long. Therefore, passive insulation alone cannot solve the problem of safety for shutdown pipeline and active heating method is needed to extend the maximum safe shutdown time.

The steady-state temperature distribution of the fluid along the pipeline length under different heating power is shown in Fig.5. It can be seen that the produced temperature diminishes with the enlargement of the pipeline distance when the heating power is less than 130 W/m. However, as the power continues to raise, the temperature drop becomes smaller and smaller. Compared with the unheated pipelines, the temperature of the fluid enhances by 18.89°C, 26.45°C, 37.79°C, 49.13°C, 56.69°C, 68.03°C at the position of 15km when the heating power is 50 W/m, 70 W/m, 100W/m, 130W/m, 150 W/m and 180W/m, respectively. The temperature of the fluid at the end of the pipeline is 31.48°C, which is higher than the critical temperature of 30°C under normal transportation conditions with the heating power of 50 W/m, indicating that the electric heating method can effectively solve the problem of the flow security in submarine long transmission pipeline. The fluid temperature enhances slowly with the enlargement of the pipeline distance for the heating power of 150 W/m, indicating that the heat lost by the fluid to the outside environment is less than the heat generated by Joule heat. The fluid temperature at the end of the pipeline is 20°C higher than the initial temperature and rises significantly for the heating power of 180 W/m. However, the heating power is not as high as possible in practical engineering applications. It is necessary to consider the economy and need to ensure that the outlet fluid temperature of the pipeline is greater than the critical temperature.

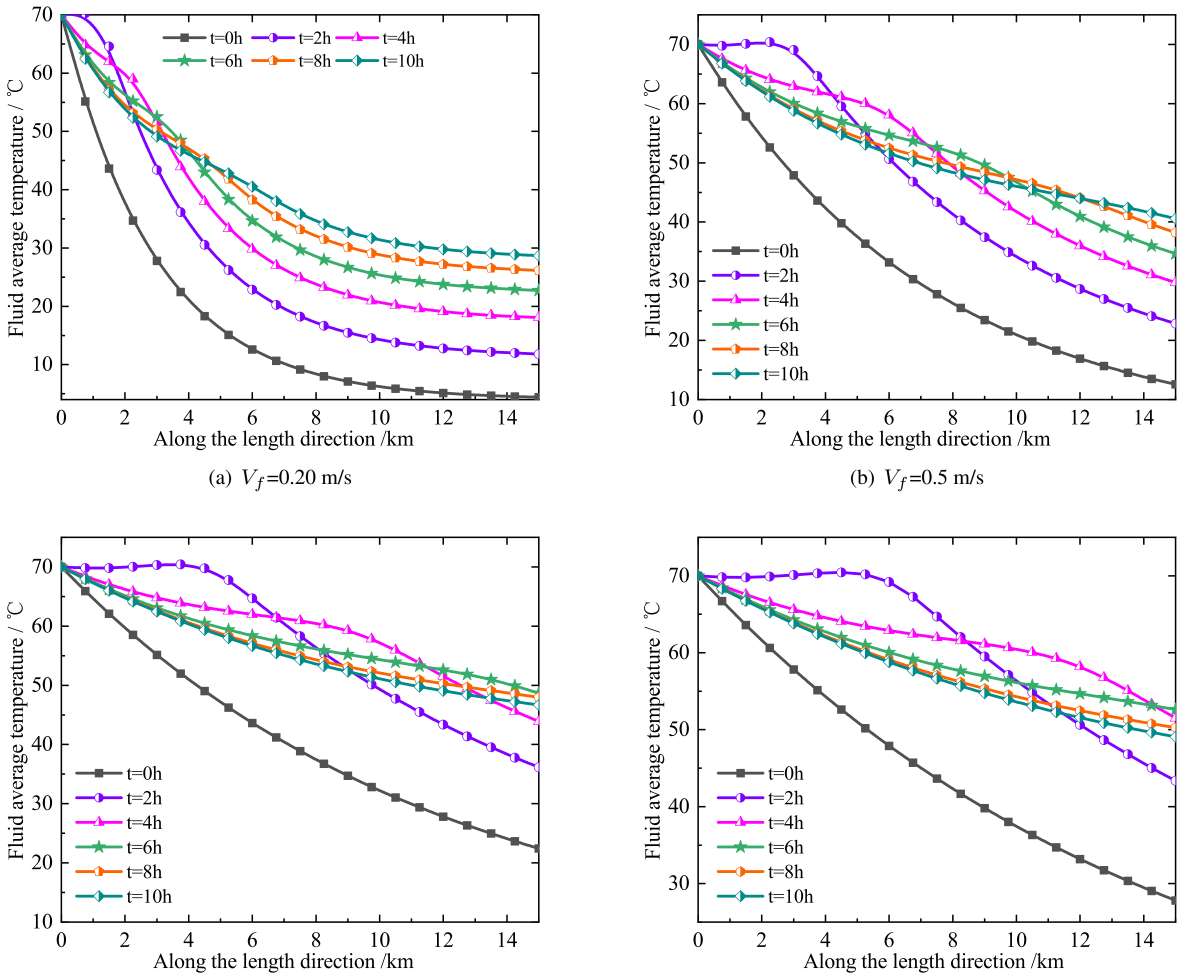


(a) P=50 W/m (b) P=100 W/m (c) P=150 W/m (d) P=180 W/m

Figure 6. Temperature distribution of the produced fluid under the start-up conditions with different heating power.

The variation for comparing the average temperature of the fluid along the length direction under different heating power is shown in Fig.6. The results showed under the same heating power, the average temperature of the fluid at the end of the pipeline raises with the extension of heating time, especially more obvious under high heating power. The longer the heating time, the farther the position where the temperature of the fluid began to drop is farther away from the inlet for specific heating power. It can be seen from the distribution trends of each curve that the temperature in the early stage of the pipeline rises slightly, after that gradually parallel to the natural temperature drop curve and showed a downward trend with the enlargement of the distance along the pipeline. The influence of heating power on the average temperature of the fluid will be enhanced by the heating time of $6h$, $8h$ and $10h$. Finally, the temperature along the flow is close to the steady state after 10 hours, indicating that electric heating technology takes certain time to achieve the ideal effect.

The comparative variation curve of the average temperature along length direction under different flow rates as shown in Fig.7. It can be seen that the variation trend of the average temperature of the fluid along the length direction of the pipeline for the flow rate of 0.2m/s is obviously different from that under other flow rates. This is because the changes in flow rate will lead to the downward rate and the trend of fluid temperature in natural conditions. At the same time, the average temperature of the fluid gradually declines with the accumulation of heating time and then approaches the steady state under the same flow rate. The faster the flow rate, the shorter the time required to reach the steady-state distribution, and the impact of heating time on the average temperature of the fluid will gradually weaken. When the heating time is 0h, the flow rate is 0.2m/s, 0.5m/s, 0.8m/s and 1.0m/s respectively, the fluid temperature at the end of the pipeline is 4.4°C, 12.58°C, 22.45°C and 27.80°C respectively, indicating that the temperature rises with the enlargement of flow rate and shows a significant upward trend as a whole without heating. The reason is that the dissipation time of high-temperature fluid per unit volume to the outside environment reduces with the enlarge of flow rate, as well as the



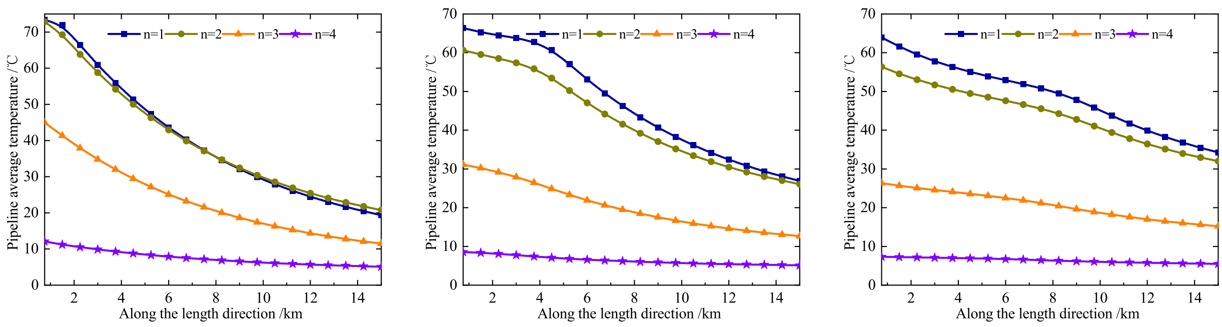
(a) V_f=0.20 m/s

(b) V_f=0.5 m/s

(c) V_f=0.80 m/s

(d) V_f=1.0 m/s

Figure 7. Temperature distribution of the produced fluid under the start-up conditions with different flow rates.



(a) t=1h

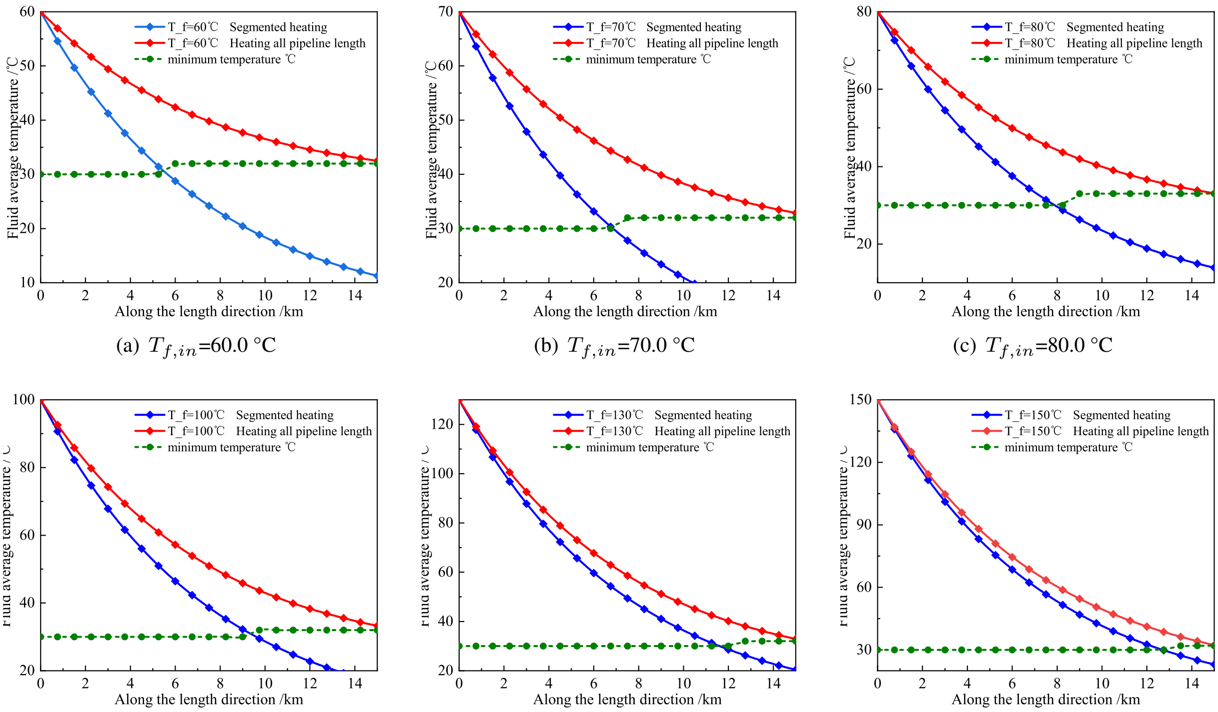
(b) t=3h

(c) t=6h

Figure 8. Temperature distribution of each layer in pipeline along the length direction under different heating times.

amount of heat dissipation diminishes. As time continues to accumulate, the growth in the average temperature of the fluid becomes smaller, indicating that the heat carried by the fluid is basically equivalent to the heat exchanged between the fluid and the external environment, then the fluid temperature field eventually tends to be steady.

Figure 8 shows the temperature distribution of each layer in pipeline along the length direction under different heating times. From the previous introduction, the first layer is the inner lining layer, the second is electric heating layer, the third is the fiber reinforcement layer and the fourth is the outer protective layer. The inner lining layer and the outer protective layer are made of the same materials. The temperature of each layer of is obviously different along the length direction and gradually minimizes, except for the outer protective layer. The temperature distribution of the inner lining layer and the electric heating layer in pipeline are very similar, that is because the heat needs to be transferred from the heating layer through the inner lining layer to the produced fluid, so the temperature of the inner lining layer is also high to achieve the effect of heating the fluid. With the of heating time, the temperature of the inner lining layer and heating layer gradually rises and the rate of decline slows down, which reflected on the raise of the temperature at the end of the pipeline. However, the temperature of the fiber reinforcement layer and the outer protective layer of the pipe is not sensitive to heating and unchanged, especially the temperature of the outer protective layer which is slightly higher than the ambient fluid temperature. This occurrence is a result of the expectation that the heat follows its purpose of being transmitted to the inner part of the fluid, and not to the outer part, which will consume a certain amount of heat and reduce the heat transfer effect. Therefore, the temperature of the outer layer is not related to heating.



(a) $T_{f,in}$=60.0 °C (b) $T_{f,in}$=70.0 °C (c) $T_{f,in}$=80.0 °C

(d) $T_{f,in}$=100.0 °C (e) $T_{f,in}$=130.0 °C (f) $T_{f,in}$=150.0 °C

Figure 9. Variation diagram of fluid temperature distribution along the pipeline at different initial temperatures.

Table 3. Comparison of segmented heating and overall heating at different initial temperatures

Initial temperature/°C	50	60	70	80	100	130	150
The position where begins to heat /m	4196	5642	6851	7888	9606	11606	12690
Overall heating power per unit length /(W/m)	58.81	56.14	53.69	50.87	44.35	33.00	24.66
Segmented heating power per unit length /(W/m)	59.84	59.84	59.84	59.84	59.84	59.84	59.84
Total power of segmented heating /MW	0.6466	0.5600	0.4877	0.4256	0.3228	0.2031	0.1383
Total power of heating all pipeline /MW	0.8717	0.8421	0.8054	0.7630	0.6653	0.4950	0.3698
Energy-saving efficiency /%	25.83	33.50	39.45	44.22	51.48	58.97	62.61

Table 4. Comparison of segmented heating and overall heating with different pipeline length

Pipeline length /km	10	15	20	25	30
The position where begins to heat /m	6850	6850	6850	6850	6850
Overall heating power per unit length /(W/m)	31.12	53.69	64.98	71.48	76.26
Segmented heating power per unit length /(W/m)	59.84	59.84	59.84	59.84	59.84
Total power of segmented heating /MW	0.1884	0.4877	0.7869	1.0861	1.3853
Total power of heating all pipeline /MW	0.3112	0.8054	1.2995	1.7937	2.2878
Energy-saving efficiency /%	39.45	39.45	39.45	39.45	39.45

The initial temperature of the fluid is 60°C, 70°C, 80°C, 100°C, 130°C and 150°C with the flow rate of 0.5m/s and the length of 15km for comparative analysis as shown in Fig.9. It can be seen that the smaller the initial temperature at the same flow rate and pipeline length, the longer distance the starting heating position, that is, the larger the heating

Table 5. Comparison of segmented heating and overall heating with different fluid velocity

Fluid velocity /(m/s)	0.2	0.4	0.6	0.8	1.0
The position where begins to heat /m	2819	5509	8191	10870	13547
Overall heating power per unit length /(W/m)	78.07	62.21	45.02	27.44	9.69
Segmented heating power per unit length /(W/m)	58.17	59.53	60.06	60.34	60.52
Total power of segmented heating /MW	0.7086	0.5650	0.4089	0.2492	0.0879
Total power of heating all pipeline /MW	1.1703	0.9332	0.6753	0.4116	0.1453
Energy-saving efficiency /%	39.45	39.45	39.45	39.45	39.45

interval. The heating position, required unit length heating power and total power at different initial temperatures are shown in Table 3. It can be seen that the total power required for overall heating and segmented heating decreases with the growth of the initial temperature, indicating the fluid with high initial temperature carries more heat under the same conveying conditions, also the heat needs to be supplemented by the outside environment is reduced. The per unit length heating power is independent of the initial temperature of the fluid because of the overall heat transfer coefficient and minimum critical temperature of the pipeline remain unchanged. For example, the overall heating method requires a power of 53.69W/m to keep the produced fluid temperature of the whole pipeline higher than critical temperature 30°C for the initial temperature of 70°C, and the total power for 15km is 0.805MW. Using the method of segmented heating, 6.844km of the pipeline can be calculated without heating. Starting from this position, the power of 59.84W/m is required to heat remaining 8.155km to keep the temperature above the critical value, and the total power is 0.4876MW. When the initial temperature are 50, 60, 70, 80°C, 100°C, 130°C and 150°C, the energy-saving efficiency of segmented heating are 25.83%, 33.50%, 39.45%, 44.22%, 51.48%, 58.97% and 62.61% respectively, which means that the higher the initial temperature, the more certain the energy-saving efficiency. Table 4 and 5 show the power comparison of the two methods of segmented heating and overall heating with different pipeline distance and fluid flow rate. It can be seen that the longer the distance of the pipeline, the greater the required heating power; the greater the flow rate of the fluid, the closer the position from the inlet to the end of the pipeline, also the power required for heating is greatly reduced, indicating that there is no necessary to heat the pipeline for the large flow rate under certain working conditions.

5. CONCLUSIONS

In this paper, the transient heat transfer of the fluid in multi-layer thermoplastic composite pipes was numerically solved using the lumped parameter method combined with the finite difference method. The average temperature of the produced fluid along the length direction in pipeline under start-up and shutdown conditions were analyzed, as well as discussed the influence of different flow rates and heating power on average temperature of the fluid. The average temperature of the fluid showed a downward trend along the length direction, meanwhile the temperature gradually paralleled to the natural temperature drop curve with the enlargement of the distance under different heating power, reflecting in the speed of decline. The greater the heating power and faster the flow rate, the shorter the time required to reach the steady state temperature. There is no need to heat when the flow rate is high. Secondly, we present a global heat balance analysis of typical deep-water pipelines for oil and gas production and show that active heating is necessary for long pipelines due to limitations of passive thermal insulation method. Based on this, a segmented heating method that minimises the power requirement for a given minimum temperature of fluid was proposed, which reduces by 38.45% from the amount if adopting uniform all through heating. In short, the segmented heating method can significantly reduce the power under the condition of guaranteed flow.

6. ACKNOWLEDGEMENTS

This work was funded by the National Natural Science Foundation of China (Grant No. 51879271), the China Scholarship Council (CSC, No. 202306440017), CNPq, CAPES, and FAPERJ.

7. REFERENCES

An, C. and Su, J., 2013. "Lumped parameter model for one-dimensional melting in a slab with volumetric heat generation". *Applied thermal engineering*, Vol. 60, No. 1-2, pp. 387–396. doi:10.1016/j.applthermaleng.2013.07.018.

Barbosa, T., Bastos, R., De Boer, H. and Rojas-Díaz, R., 2019. "Thermoplastic composite pipes: A reliable cost-effective solution for pre-salt". In *Offshore Technology Conference Brasil*. OnePetro. doi:10.4043/29819-MS.

Bautista, O., Mendez, F. and Campos, I., 2005. "Transient heat conduction in a solid slab using multiple-scale analysis". *Heat and mass transfer*, Vol. 42, pp. 150–157. doi:10.1007/s00231-005-0005-6.

Bechiri, M. and Mansouri, K., 2016. "Analytical study of heat generation effects on melting and solidification of nanoenhanced PCM inside a horizontal cylindrical enclosure". *Applied Thermal Engineering*, Vol. 104, pp. 779–790. doi:10.1016/j.applthermaleng.2016.05.105.

Crepeau, J. and Siahpush, A.S., 2012. "Solid–liquid phase change driven by internal heat generation". *Comptes Rendus Mécanique*, Vol. 340, No. 7, pp. 471–476. doi:10.1016/j.crme.2012.03.004.

Davies, P., Riou, L., Mazeas, F. and Warnier, P., 2005. "Thermoplastic composite cylinders for underwater applications". *Journal of Thermoplastic Composite Materials*, Vol. 18, No. 5, pp. 417–443. doi:10.1177/0892705705054397.

De Monte, F., 2002. "An analytic approach to the unsteady heat conduction processes in one-dimensional composite media". *International Journal of Heat and Mass Transfer*, Vol. 45, No. 6, pp. 1333–1343. doi:10.1016/S0017-9310(01)00226-5.

Hastie, J.C., Guz, I.A. and Kashtalyan, M., 2022. "Numerical modelling of spoolable thermoplastic composite pipe (TCP) under combined bending and thermal load". *Ships and Offshore Structures*, Vol. 17, No. 9, pp. 1975–1986. doi:10.1080/17445302.2021.1958534.

Jain, P.K. and Singh, S., 2009. "Analytical solution to transient asymmetric heat conduction in a multilayer annulus". doi:10.1115/1.2977553.

Jain, P.K. and Singh, S., 2010. "An exact analytical solution for two-dimensional, unsteady, multilayer heat conduction in spherical coordinates". *International Journal of Heat and Mass Transfer*, Vol. 53, No. 9-10, pp. 2133–2142. doi: 10.1016/j.ijheatmasstransfer.2009.12.035.

Li, M. and Lai, A.C., 2013. "Analytical solution to heat conduction in finite hollow composite cylinders with a general boundary condition". *International Journal of Heat and Mass Transfer*, Vol. 60, pp. 549–556. doi: 10.1016/j.ijheatmasstransfer.2013.01.029.

Lu, X., Tervola, P. and Viljanen, M., 2006a. "Transient analytical solution to heat conduction in composite circular cylinder". *International Journal of Heat and Mass Transfer*, Vol. 49, No. 1-2, pp. 341–348. doi: 10.1016/j.ijheatmasstransfer.2005.06.019.

Lu, X., Tervola, P. and Viljanen, M., 2006b. "Transient analytical solution to heat conduction in multi-dimensional composite cylinder slab". *International Journal of Heat and Mass Transfer*, Vol. 49, No. 5-6, pp. 1107–1114. doi: 10.1016/j.ijheatmasstransfer.2005.08.033.

Lu, X., Tervola, P. and Viljanen, M., 2005. "A new analytical method to solve the heat equation for a multi-dimensional composite slab". *Journal of Physics A: Mathematical and General*, Vol. 38, No. 13, p. 2873. doi:10.1088/0305-4470/38/13/004.

Morozov, E.V. and Yu, K., 2016. "Design and analysis of flexible reinforced thermoplastic pipes (RTPs) for offshore oil and gas applications". In *The Twelfth ISOPE Pacific/Asia Offshore Mechanics Symposium*. OnePetro.

Sadat, H., 2006. "A second order model for transient heat conduction in a slab with convective boundary conditions". *Applied thermal engineering*, Vol. 26, No. 8-9, pp. 962–965. doi:10.1016/j.applthermaleng.2005.10.013.

Singh, S. and Jain, P.K., 2008. "Analytical solution to transient heat conduction in polar coordinates with multiple layers in radial direction". *International journal of thermal Sciences*, Vol. 47, No. 3, pp. 261–273. doi: 10.1016/j.ijthermalsci.2007.01.031.

Su, G., Tan, Z. and Su, J., 2009. "Improved lumped models for transient heat conduction in a slab with temperature-dependent thermal conductivity". *Applied Mathematical Modelling*, Vol. 33, No. 1, pp. 274–283. doi: 10.1016/j.apm.2007.11.007.

Su, J., Cerqueira, D.R. and Wang, S.Z., 2012. "Thermal design of multi–layered composite pipelines for deep water oil and gas production". *International journal of computer applications in technology*, Vol. 43, No. 3, pp. 248–259. doi:10.1504/IJCAT.2012.046311.

Sunday, N., Settar, A., Chetehouna, K. and Gascoin, N., 2021. "An overview of flow assurance heat management systems in subsea flowlines". *Energies*, Vol. 14, No. 2, p. 458. doi:10.3390/en14020458.

Sundén, B., 1986. "Transient heat conduction in a composite slab by a time-varying incident heat flux combined with convective and radiative cooling". *International communications in heat and mass transfer*, Vol. 13, No. 5, pp. 515–522. doi:10.1016/0735-1933(86)90028-X.

Tan, Z., Su, G. and Su, J., 2009. "Improved lumped models for combined convective and radiative cooling of a wall". *Applied Thermal Engineering*, Vol. 29, No. 11-12, pp. 2439–2443. doi:10.1016/j.applthermaleng.2008.12.039.

Viot, L., Saas, L. and De Vuyst, F., 2018. "Solving coupled problems of lumped parameter models in a platform for severe accidents in nuclear reactors". *International Journal for Multiscale Computational Engineering*, Vol. 16, No. 6. doi: 10.1615/IntJMultCompEng.2018025643.

Wilkins, J., 2018. "Qualification of Thermoplastic Composite Pipes". In *International Conference on Offshore Mechanics and Arctic Engineering*. American Society of Mechanical Engineers, Vol. 51241, p. V005T04A037. doi: 10.1115/OMAE2018-77014.

8. RESPONSIBILITY NOTICE

The authors are solely responsible for the printed material included in this paper.