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Simulation of Transient Heat Transfer of Sandwich Pipes With Active Electrical Heating

This paper presents an analysis of transient heat transfer in sandwich pipelines with active electrical heating. The mathematical models governing the heat conduction in the composite pipeline and the energy transport in the produced fluid were solved by using finite difference methods. Numerical results of computational simulation of cool-down for three sandwich pipeline configurations under typical production conditions were presented. The analysis showed that the sandwich pipe with active heating is a viable solution to meet severe flow assurance requirements of ultra-deepwater oil production even under unplanned and prolonged cool-down conditions. [DOI: 10.1115/1.2073090]

Keywords: pipeline technology, flow assurance, active electrical heating, pipe-in-pipe, thermal analysis

1 Introduction

Flow assurance in deepwater conditions is an essential part of pipeline technology for offshore oil and gas production [1]. Flow assurance addresses all relevant issues in the reliable, manageable, and economical transport of the produced fluid from the reservoir to the processing plant. High hydrostatic pressure and low environmental temperature create major technological challenges for the design of flowlines and risers. Three main factors may contribute to the low temperature of produced fluid in ultra-deepwater environments: shallow reservoirs, long tie-back distance, and the large adiabatic temperature drop associated with the pressure drop along the height of the riser. Flow assurance requires that the temperature of the produced fluid be kept above the paraffin deposition temperature (around 39°C typically) during steady-state production and above the gas hydrate formation temperature (around 20°C typically) during warm-up or cool-down periods. It is mandatory that passive thermal insulation be used in all deepwater flowlines for multiphase production of oil and gas as it is the most economical method to prevent hydrate formation and wax deposition. In steady-state conditions, passive insulation alone may attend flow assurance requirements, but during transient events such as warm-up and cool-down or in exceptional situations such as plant shutdown, curative solutions are often used. These methods can sometimes become complicated and expensive. Active heating is required when passive thermal insulation alone is not sufficient to prevent wax deposition and hydrate formation.

Pipe-in-pipe (PIP) systems have been proposed lately as a viable solution to meeting the flow assurance requirements of deepwater oil and gas production [2–4]. They consist of two concentric metal pipes in which the annulus is either filled with a nonstructural insulating material or is used to carry water for well injection, umbilical cables, etc. Usually, internal and external pipes are designed independently against failure under internal and external pressures, respectively, combined with installation loads, mainly longitudinal bending. The factors governing the collapse and propagation of buckles in single pipes and pipe-in-pipe systems under external pressure have been extensively studied in the past, so that, nowadays, deepwater pipes can be safely designed [5–9].

Two methods of active heating of deepwater pipelines have been studied in recent years: circulating water heating and electrical heating. British Petroleum (BP) planned to develop the King project in Mississippi Canyon Block 85 (MC85) via a dual-well, subsea production scheme [10]. The active heating system employs hot water circulating in the closed loop in the annulus of a dual, 219×324 mm^2 (8×12 in.^{2}) PIP system. External insulation around the jacket pipe and burial/backfill provides thermal insulation for the flowlines. Heat is extracted from the exhaust waste heat of three, 3.9 MW, electrical generator turbine drivers. A detailed model using the software OLGA was developed to investigate the feasibility of the circulating water heating system, which indicated that circulation of 3180 m^3 heated water departing the TLP (Tension Leg Platform) at 66°C results in acceptable temperature profiles for the production scenarios of King project. Zhang et al. [11] discussed the thermal analysis and design of hot-water-heated production flowline bundles using two typical offshore West Africa developments as case studies. Factors affecting the warm-up time, such as water flowrate and temperature, pressure limitations, and topsides heating capacities, were analyzed and compared. Secher and Felix-Henry [12] presented a flexible pipe structure termed IPB (integrated production bundle), which is a flexible riser assembly based on integrated service umbilical (ISU) technology and other technologies, incorporating active heating, gas lift hoses, and passive insulation. Both heat tracing technologies are qualified for IPB's: electrical and hot water circulation. No immediate preferred solution was indicated as both have their advantages. Electrical heat traces give an even distribution of energy along the IPB while the hot water brings more heat at the top end where it is most needed. The main advantage of electrical heat tracing over hot water circulation is that it is much more compact regarding the design of the IPB. A system equipped with the heat tracers in the armor layers will have the same OD as a conventional insulated flexible pipe. This technology also enables the use of standard flexible pipe insulation. The limitations of the heat tracing armors concept will be on the maximum heat power available and/or the maximum length achievable because of the small cross section of conductors.

Active electrical heating can be further classified into direct and indirect heating. The direct electrical heating system is based on the fact that an electric current in a metallic pipe generates heat. Norwegian oil companies, cable manufacturers, and pipeline installation companies have conducted studies on direct electrical

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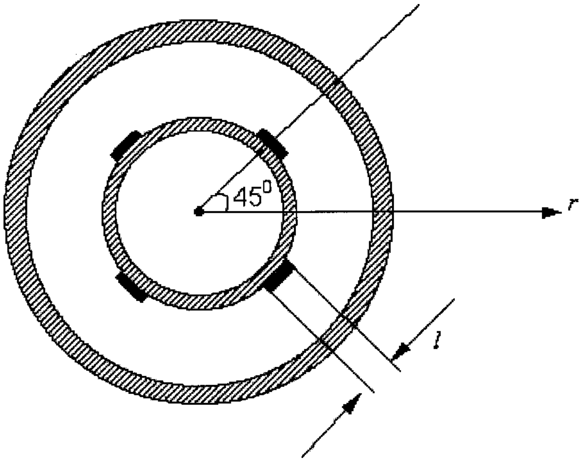

Fig. 1 Cross section of a sandwich pipeline with active heating by four strips of electrical heater

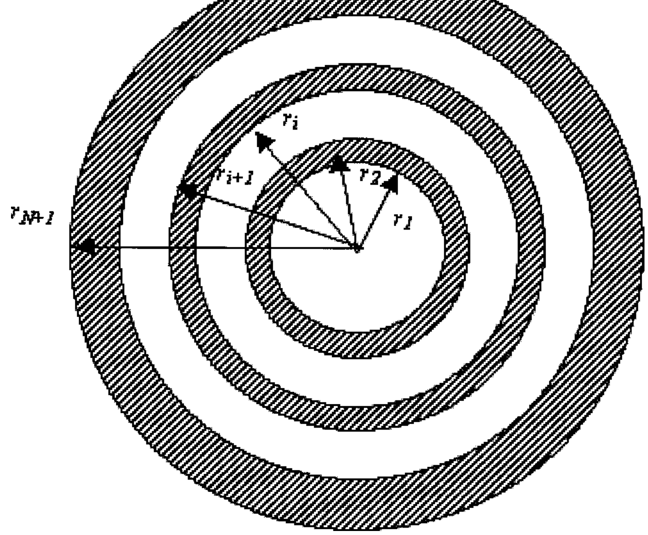

Fig. 2 Cross section of a multilayered composite pipeline

heating of multiphase subsea pipelines and risers to prevent hydrate formation and wax plugs [13–15]. The evaluation of technical feasibility and cost estimates have been done for a 50 Hz direct resistive heating system and for a system based on electromagnetic induction. The electrical rating of the systems depends basically on heating requirement, pipe material, and pipeline length. The feasibility of the concepts has been verified through full scale subsea tests. Results from the measurements were used to determine the characteristic parameters of two systems installed in the North Sea. By indirect or electrical trace heating, electric current is applied to resistive cables which are electrically insulated from the metallic pipe. Laouir and Denniel [16] presented a heated pipe-in-pipe system in which heating is generated by resistive cables using low voltage, which complements the insulating performance of pipe-in-pipe. Su and Cerqueira [17] developed a mathematical model for analysis of transient heat transfer in multilayered composite pipeline during warm-up and cool-down. Su et al. [18] presented a thermal analysis of combined active heating and passive insulation of deepwater pipelines and proposed a heating method that minimizes the power requirement for a given minimum temperature of produced fluid. In a subsequent work [19], a new concept was proposed to combine thermal insulation and active heating by inserting strips of electrical resistance into the sandwich pipes. Initially, a global heat balance analysis to determine the energy input requirement was done and then a steady-state thermal analysis to determine the temperature distribution in a cross section of the sandwich pipes under typical production conditions in ultra deepwater. A mathematical model was developed for the analysis of steady-state heat transfer in the sandwich pipes.

In this work, the analysis of transient heat transfer in the sandwich pipelines with active electrical heating is presented. The mathematical models governing the heat conduction in the composite pipeline and the energy transport in the produced fluid are solved by using finite difference methods. As unplanned cool-down of the pipelines is most critical to safe and economical operation of pipelines in deep and ultra-deepwater conditions, numerical results of computational simulation of cool-down for three sandwich pipeline configurations under typical production conditions are presented.

2 Physical Problem and Mathematical Modeling

Consider a sandwich pipeline composed of two concentric metal pipes with thermal insulation material in the annulus. Four strips of electrical heater are located symmetrically over the outer surface of the inner metal pipe, as shown in Fig. 1. The heating system is basically composed by copper cables grouped in sets distributed around the flowline. The heat input is produced by the electrical activation of the resistive heating cables.

Heat Conduction in Composite Pipeline. A composite medium consisting of N concentrically cylindrical layers, shown in Fig. 2, has been considered. Each layer is assumed to be homogeneous, isotropic, and with constant thermal properties. The adjacent layers are assumed to be in perfect thermal contact. The mathematical formulation of the one-dimensional heat conduction problem is written as

$$\frac{\partial T_i}{\partial t} = \frac{\alpha_i}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_i}{\partial r}\right) + \frac{g_i(r,z,t)}{\rho_i c_{pi}}, \quad r_i < r < r_{i+1}, \quad i = 1,\ldots,N \tag{1}$$

where $T_i(r,t)$ is the temperature in the ith layer, $\alpha_i = k_i/\rho_i c_{pi}$ is its thermal diffusivity, k_i is the thermal conductivity, ρ_i is the density, and c_{pi} is the specific heat. The inner and outer radii of the ith layer are r_i and r_{i+1}, respectively.

Equation (1) is to be solved with the following boundary and interface conditions:

$$-k_i\frac{\partial T_1}{\partial r} = h_1(T_f - T_1) \quad \text{at } r = r_1 \tag{2}$$

$$-k_n\frac{\partial T_N}{\partial r} = h_a(T_N - T_m) \quad \text{at } r = r_{N+1} \tag{3}$$

$$T_i = T_{i+1} \quad \text{at } r = r_{i+1}, \quad i = 1,\ldots,N \tag{4}$$

$$k_i\frac{\partial T_i}{\partial r} = k_{i+1}\frac{\partial T_{i+1}}{\partial r} \quad \text{at } r = r_{i+1}, \quad i = 1,\ldots,N \tag{5}$$

where T_f is the temperature of the fluid transported in the pipeline, h_1 is the heat transfer coefficient between the innermost layer and the fluid inside it, T_m is the temperature of the environmental fluid, and h_a is the heat transfer coefficient between the outermost surface and environmental fluid.

The initial conditions for temperatures in each layer are

$$T_i(r,0) = T_{i0}(r), \quad r_i \leqslant r \leqslant r_i + 1, \quad i = 1,\ldots,N \tag{6}$$

In this work, we solved the boundary value problem consisting of Eqs. (1)–(6) using the second-order-accurate Crank-Nicolson finite difference method.

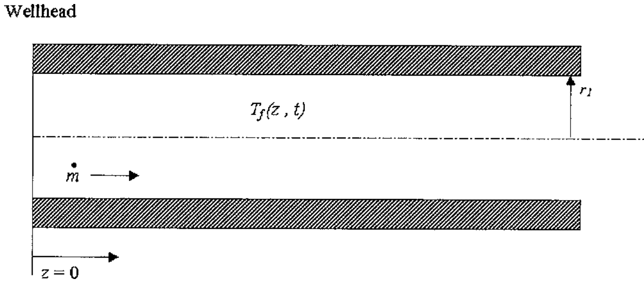

Fig. 3 Longitudinal view of a pipeline

Energy Transport in Produced Fluid. Neglecting the effects of flow transient, we consider a steady, fully developed flow with an average velocity u of a produced fluid with constant properties in a pipeline of circular transversal section, as shown in Fig. 3. The one-dimensional transient energy equation for the produced fluid is written as

$$\frac{\partial T_f}{\partial t} + u\frac{\partial T_f}{\partial z} = -\frac{2q_{r_1}}{r_1 \rho_f c_{pf}} \tag{7}$$

and heat flux in the inner surface of the pipeline is given by

$$q_{r_1} = h_1(T_f - T_{r_1}), \tag{8}$$

where ρ_f is the density of the produced fluid, c_{pf} is its specific heat, r_1 is the inner diameter of the pipeline, T_{r_1} is the wall temperature, and h_1 is the heat transfer coefficient between the flow and the pipeline.

Equation (7) is to be solved with an initial temperature distribution of the fluid along the pipeline of length L and an inlet boundary condition in the wellhead

$$T_f(z,0) = T_{f0}(z) \quad \text{at } t=0 \tag{9}$$

$$T_f(0,t) = T_{f_{in}} \tag{10}$$

The mathematical model formed by Eqs. (7)–(10) was solved by a second-order-accurate explicit finite difference scheme initially developed by Warming and Beam [20].

3 Results and Discussion

Due to the lack of more realistic pipeline and production well data, hypothetical conditions were applied for sandwich pipelines with inner diameter of 6 in. (0.1524 m). The pipelines are in sandwich pipe configuration with internal and external steel pipes and with polypropylene as thermal insulation material in the annulus. The geometrical properties of the pipelines are given in Table 1. The thermophysical properties of the pipelines are given in Table 2. The wellhead temperature of produced fluid was taken as 76°C and the sea water as 4.0°C. A mass flow rate of 14.72 kg/s was assumed with a constant density of 800 kg/m^3 and a specific heat of 2700 J/kg°C.

For all three configurations of sandwich pipelines, the transient thermal behavior of the pipelines and the produced fluid during cool-down were simulated, first without active electrical heating, then with electrical heating. The results are shown in Figs. 4–9. For cool-down with active electrical heating, the required minimum temperature of the produced fluid was 25°C.

It can be noted from Fig. 4 that for case 1 without active heating, the produced fluid temperature dropped to below 20°C near the pipeline exit after 1 h. The produced fluid temperature was well below 20°C for all the pipeline length after 2 h. After 4 h, the produced fluid temperature approached the temperature of the environmental fluid. However, it can be seen from Fig. 5 that when the pipeline was operated with active heating, the produced fluid temperature dropped to approximately 25°C after 1 h and kept the value of 25°C afterwards. The required linear heat generation rate was 275.8 W/m and the total power requirement was 1.38 MW.

Table 1 Geometrical properties of the composite pipelines

Case	δ_1 (mm)	δ_2 (mm)	δ_3 (mm)	L (km)
1	3.175	25.4	3.175	5.0
2	3.175	50.8	3.175	10.0
3	3.175	76.2	3.175	16.0

Table 2 Thermophysical properties of the composite pipelines

Material	ρ (kg/m^3)	c_p (J/kg°C)	k (W/m°C)
Stainless steel	7850	486	54
Polypropylene	775	2000	0.17

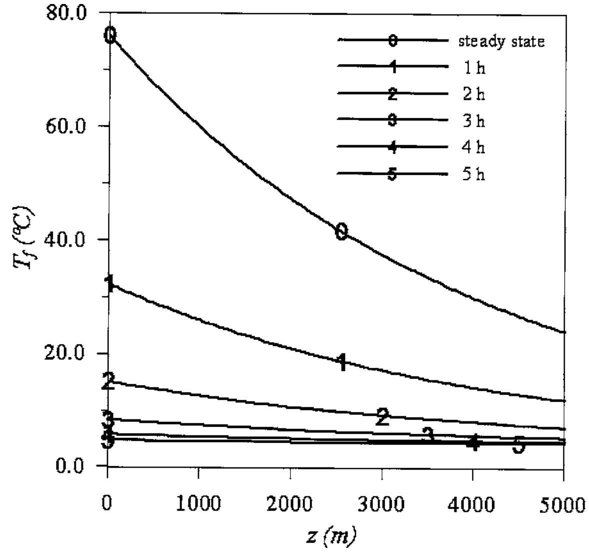

Fig. 4 Case 1: temperature distributions of the produced fluid during cool-down without active heating

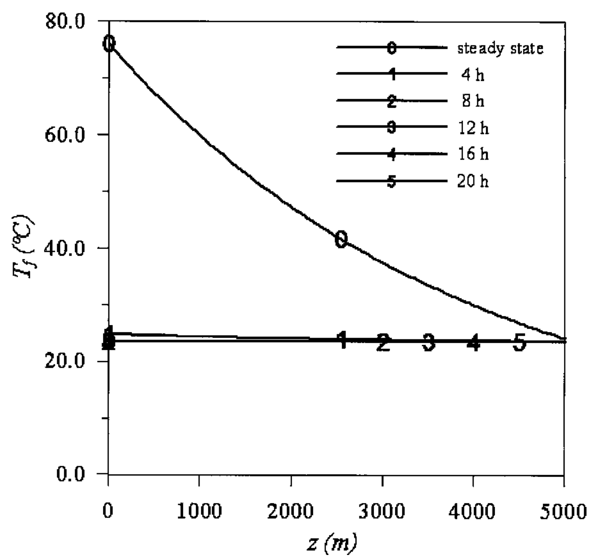

Fig. 5 Case 1: temperature distributions of the produced fluid during cool-down with active heating

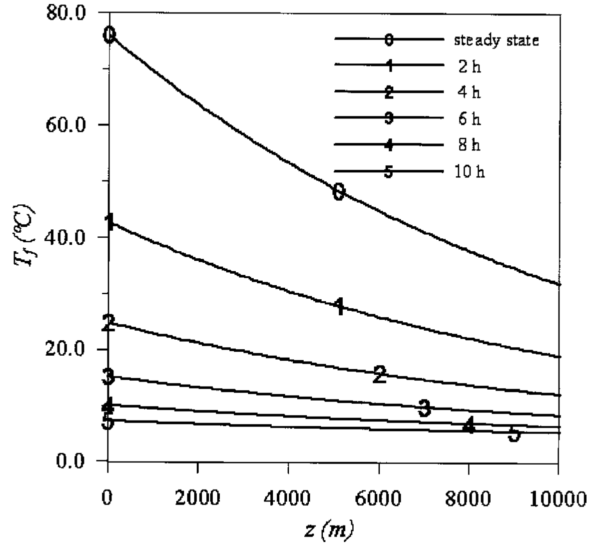

Fig. 6 Case 2: temperature distributions of the produced fluid during cool-down without active heating

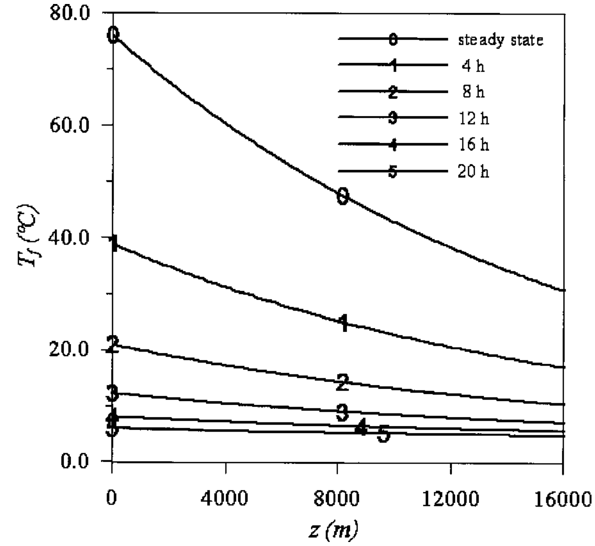

Fig. 8 Case 3: temperature distributions of the produced fluid during cool-down without active heating

In case 2, the pipeline was 10 km long and the thermal insulation layer was 2 in. thick. The performance of the pipeline during cool-down without and with active electrical heating was shown in Figs. 6 and 7. With a thicker thermal insulation layer, the produced fluid temperature was maintained above 20°C for roughly 4 h and dropped to 4°C after 10 h, if no active heating was used. With active heating, the produced fluid temperature approached the required minimum value after 3 h. The required linear heat generation rate was 104.1 W/m and the total power requirement was 1.04 MW.

In case 3, the pipeline was 16 km long and the thermal insulation layer was 3 in. thick. The performance of the pipeline during cool-down without and with active electrical heating was shown in Figs. 8 and 9. With the thickest thermal insulation layer considered, the produced fluid temperature dropped to below 20°C after roughly 8 h and dropped to 4°C after 20 h, if no active heating was used. With active heating, the produced fluid temperature approached the required minimum value after 20 h. The required linear heat generation rate was 68.0 W/m and the total power requirement was 1.09 MW.

4 Conclusion

In this work, computational simulation of transient thermal events during cool-down of sandwich pipelines with polypropylene as thermal insulation material was presented. For the three pipeline configurations considered, numerical results indicated that although the passive thermal insulation was adequate for steady-state production conditions, the active heating was required during either planned or unplanned cool-down. For case 1, the active heating was definitely required for prevention of gas hydrate formation, as the produced fluid temperature dropped to below 20°C along the whole pipeline after only 2 h. For case 2, the produced fluid temperature dropped to 20°C after roughly 4 h thus active heating was also required if the required shut-down period was 8 h. For case 3, active heating was necessary if prolonged shut-down occurred, although the produced fluid temperature was

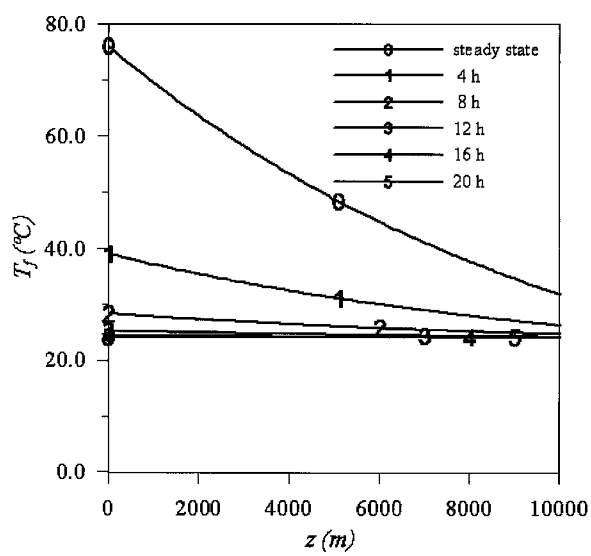

Fig. 7 Case 2: temperature distributions of the produced fluid during cool-down with active heating

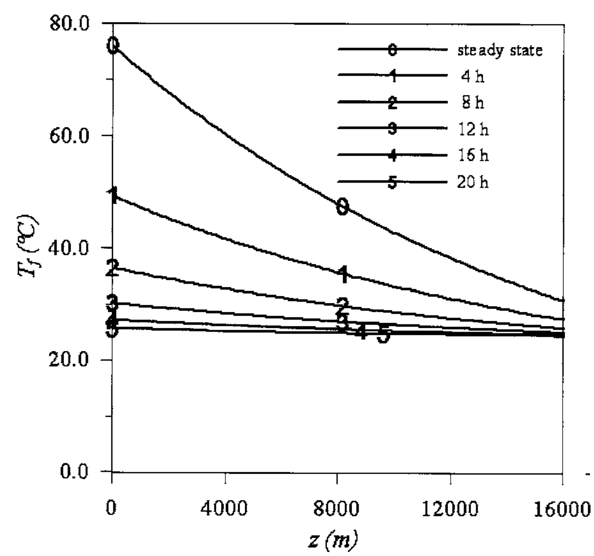

Fig. 9 Case 3: temperature distributions of the produced fluid during cool-down with active heating

kept above 20°C for 8 h without active heating. By comparing the three cases simulated, it can be noted that the power requirement per unit length was smaller if the thermal insulation layer was thicker. A compromise should be achieved in the pipeline specifications by considering both the higher capital expenses associated with thicker thermal insulation and the higher operational expense associated with higher power requirement. A useful tool has been presented for the thermal design and analysis of composite pipelines for oil and gas production in deep and ultra-deepwater conditions. The benefit of the simulations will increase if flow assurance culture of the pipeline operator is properly incorporated in the analyses.

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Nomenclature

c_p = specific heat
g = volumetric heat generation rate
h = heat transfer coefficient
k = thermal conductivity
L = pipeline length
N = number of layers
$\dot{q}$ = heat flux
r = radial coordinate
U = overall heat transfer coefficient
u = average fluid velocity
T_m = temperature of environmental fluid
T_f = temperature of produced fluid
T_i = temperature of ith layer of composite media
z = longitudinal coordinate

Greek Letters

α = thermal diffusivity
δ = thickness of a layer
ρ = density

Subscripts

i = index of composite layers
f = produced fluid
in = inlet condition
out = outlet condition

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