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A numerical approach for obtaining type curves of superheated multi-component thermal fluid flow in concentric dual-tubing wells

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ABSTRACT

Huge amount of works have been done on wellbore modeling, but most of the researchers focused on saturated thermal fluid, with very little efforts on superheated multi-component thermal fluid (SMTF). In this paper, the authors presented a novel model for predicting thermophysical properties of SMTF in concentric dual-tubing wells (CDTW).

Firstly, based on real gas state equation, a novel model comprised of mass, momentum and energy balance equation in the integral joint tubing (IJT) and annuli was proposed for CDTW. Secondly, type curves of SMTF flow in CDTW were obtained from the mathematical model mainly by finite difference method and iteration technique. Finally, validation and sensitivity analysis of the model were sequentially conducted.

The validation results showed that the predicted results were in agreement with field test results, which proved the correctness of the model. Type curves of SMTF flow in CDTW showed that the injection temperature difference between the IJT and annuli has a strong influence on the profiles of temperature and superheat degree in each tubing. According to the sensitivity analysis of the model, the superheat degree in the IJT decreases with the increase of injection pressure in the IJT, but the superheat degree in annuli does the opposite. The superheat degree in the IJT increases with the increase of injection pressure in annuli, but the superheat degree in annuli does the opposite. Both of the temperature and superheat degree in each tubing decreases with the increase of non-condensing gas content.

This paper gives the engineers a novel insight into what is the distribution characteristics of thermophysical properties of SMTF in CDTW, and provides an optimization method of injection parameters for oilfield.

1. Introduction

Thermal engineering plays an important role in industry [1–12]. And those thermal methods used in petroleum industry are proved effective by field tests. Among those methods, SAGD [13–16], as well as cyclic saturated/superheated steam stimulation [17–21] are the most widely used ones. With such thermal methods, heavy oil wells can produce at an economical rate. Therefore, hot fluid injection measures are common practices for heavy oil recovery. Undoubtedly, precisely predicting thermophysical properties of these thermal fluid in the wellbores are the first and foremost tasks for the petroleum engineers. Regrettably, the predicting tasks are never easy due to the complexity of fluid flow in the wellbores, especially in CDTW.

The studies on predicting thermophysical properties of thermal fluid in the wellbores were firstly conducted in the early 1960s [22–26]. In those years, the light crude oil was relatively rich in resources and the development of heavy oil was subjected to many restrictions. Consequently, researches in this field were relatively sparse. However, with the change of energy demand and with the progress of technology, the development of heavy oil is becoming more and more important, and the production costs are decreasing. Predicting thermophysical properties of thermal fluid in the wellbores becomes a hotspot in the petroleum industry in recent years [27–36].

Satter [37] proposed a method for calculating the steam quality considering phase change of superheated steam. But he did not consider the change of kinetic energy in the energy balance equation and proposed the assumption that the pressure drop caused

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Nomenclature

w	mass flow rate of SMTF in the wellbores, kg/s
r	tube radius, m
ρ	density of SMTF, kg/m^3
v	flow velocity of SMTF, m/s
z	well depth, m
Q	heat exchange rate between IJT and annuli, W
h	specific enthalpy of SMTF in the IJT, J/kg
θ	well angle from vertical, rad
g	gravitational acceleration, $g \approx 9.81$, m/s^2
τ_f	shear stress in the wellbores, N
Δz	the length of the segment, m
q	heat loss rate from annuli to formation per unit depth, W/m
U_{ijo}	the comprehensive heat transfer coefficient between IJT and annuli, W/(m^2·K)
T	SMTF temperaturein the wellbores, K
λ	thermal conductivity of the tubing, W/(m·K)
h_{fiji}	forced convection heat transfer coefficient on inside wall of the IJT, W/(m^2·K)
h_{fijo}	forced convection heat transfer coefficient on outside wall of the IJT, W/(m^2·K)
μ	SMTF viscosity, Pa·s

Subscripts

ij	integral joint tubing
an	annuli
i	inner radius
o	outer radius
a	inner tubing
b	outer tubing
c	casing
cem	cement sheath
in	inlet face of the segment
out	outlet face of the segment
tub	tubing
ins	insulation material

by the potential energy reduction can be offset by pressure drop caused by friction loss, which will certainly cause error. Pacheco and Farouq Ali [38] proposed a comprehensive mathematical model for predicting saturated steam pressure in the wellbores considering the influence of friction loss on the distribution of pressure in the wellbores. Then, Farouq Ali [39] developed a mathematical model predicting pressure distribution for both upward and downward flow, and proposed a formula for steam quality distribution based on the energy conservation equation. Durrant et al. [40] improved the algorithm for calculating the two dimensional transient heat conduction equation by using an iterative method.

Ejiogu et al. [41] and Tortike et al. [42] proposed empirical formulas for calculating thermal parameters of saturated steam, which brough convenience to the programming calculation. Sagar et al. [43] proposed a simple algorithm to calculate the temperature distribution of saturated steam in the wellbore. The pioneers of these techniques gave a good foundation for the follow-up studies [44–46].

Hasan and Kabir [47] developed a formation heat flow model and presented an expression of transient temperature as a function of time and distance from wellbore. Then, huge amount of studies had been done by Hasan et al. [48–55] on thermophysical properties distributions and formation heat transfer. These researches presented fundamental references for later studies [56].

Zhou et al. [57], Xu et al. [58], Gu et al. [32,33], Fan et al. [36] and Sun et al. [59] presented different models for predicting thermophysical properties of superheated steam in conventional single-tubing wells. All of these studies about thermal fluid flow in single-tubing wells lay a solid foundation for the later researches on thermal fluid flow in CDTW.

It is proved by huge of the field tests that the application of single-tubing thermal fluid injection wells can lead to serious fingering phenomena [60–62]. Therefore, concentric dual-tubing thermal fluid injection technique has been proposed to alleviate these shortcomings, and fortunately, it has been proved to be effective and economical efficiency [63].

Caetano et al. [64] developed a mechanical model for predicting pressure drop in annuli. In this study, the flow pattern conversion standard and the flow mechanism were studied separately. And this study presented a basic reference for the follow-up researches [65–70]. But these studies were focused on up-ward flow. Griston et al. [47] and Wu et al. [71] presented different mathematical models for predicting pressure drop of saturated steam in annuli based on a new concept of equivalent radius, which has been proved effective in practice [72]. Gu et al. [32] presented a new method to calculate pressure drop of saturated steam in annuli based on the improvement of equivalent radius calculation method.

Regrettably, all of these studies of thermal fluid flow in CDTW were focused on saturated steam or saturated multi-component thermal fluid and there were no efforts ever done on modeling of SMTF flow in CDTW. Dong et al. [31,73] presented different models predicting thermophysical properties of SMTF in conventional single-tubing wells. But the heat transfer characteristics in single-tubing wells are very different from that in CDTW. Dong et al. [31] proposed a concept model of SMTF flow in CDTW, but no concrete mathemeatical model or type curves in the IJT and annuli have been presented. More researches need to be conducted urgently.

In this paper, a series of researches have been conducted on the flow and heat transfer characteristics of SMTF in CDTW. The novelty of this paper lies in three aspects: (1). A novel mathematical model is proposed to predict thermophysical properties of SMTF in CDTW. (2). Type curves of SMTF flow in CDTW is obtained by finite difference method and iteration technique. (3). Effect of injection parameters on the profiles of thermophysical properties in IJT and annuli are analyzed in detail.

2. Model description

2.1. General assumptions

A schematic of the CDTW is shown in detail in Fig. 1. In order to study the flow characteristics of SMTF in CDTW, some basic assumptions are made as follows:

(1) The injection parameters are assumed to be constant during the whole injection process.
(2) SMTF flow in the IJT and annuli is assumed to be steady state.
(3) Heat loss rate from annuli to formation is assumed to be steady state.
(4) Heat transfer rate in the formation is assumed to be transient state.