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Research Paper

Numerical simulation of supercritical carbon dioxide jet at well bottom

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HIGHLIGHTS

- A new numerical model which can simulate the real flow field characteristics of supercritical CO_2 impacting jet was proposed.
- Complex coupling was achieved with the modified SIMPLE segmentation algorithm.
- The reliability of the numerical model was validated in experiment.
- The real flow field characteristics of supercritical CO_2 impacting jet were described.
- The jet flow field can be divided into five areas according to flow characteristics.

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ABSTRACT

A numerical model was developed to study the flow field characteristics of supercritical CO_2 (SC-CO_2) impacting jet at well bottom. The model took account of jet hydrodynamics, mass transfer and thermodynamic properties of SC-CO_2. Formulas of the density, viscosity and thermal conductivity of CO_2 were verified for a supercritical state, and they were embedded in a CFD model through the user defined function (UDF). Complex coupling was achieved with the modified SIMPLE segmentation algorithm, and fields of the SC-CO_2 impact flow, pressure, temperature and physical parameters were obtained. The reliability of the numerical model was validated in experiments that monitored the pressure and temperature of SC-CO_2 impacting jet using sensors. The laboratory experiments show that the model accurately predicts the temperature and pressure fields of SC-CO_2 impacting jet. SC-CO_2 impacting jet has a more obvious thermal effect on the wall without any phenomena of CO_2 freezing and blocking nozzle. The jet flow field can be divided into five areas according to flow characteristics, and the CO_2 phase state in flow field is analyzed. The established calculation method and findings reported in the paper will provide guidance for engineering applications.

1. Introduction

The application of supercritical carbon dioxide (SC-CO_2) jet in oil and gas exploration has been proposed and widely reported in the literature [1–4]. Previous research has identified many advantages of SC-CO_2 as a new drilling fluid. A schematic drawing of coiled tubing drilling with SC-CO_2 is shown in Fig. 1. SC-CO_2 can invade reservoirs without damaging them, especially in the case of water sensible reservoirs. The invading CO_2 can increase the permeability of reservoirs and enhance production and recovery [5]. At the same time, the use of CO_2 fits global environmental policy and has benefits in terms of controlling a greenhouse gas. Moreover, rock-breaking ability tests carried out by Kolle [4] indicated that SC-CO_2 jet had improved rock-breaking efficiency. The threshold pressure of SC-CO_2 jet was 2/3 that of water jet for granite and less than half that of water jet for shale.

When the temperature exceeds 31.10 °C (304.25 K) and pressure exceeds 7.38 MPa, CO_2 reaches a supercritical state. Because most oil and gas reservoirs are high-pressure and high-temperature environments, the liquid CO_2 pumped into the reservoirs can transform to a supercritical state at a certain depth [6]. However, the environments of downhole are complex, so it is difficult to simulate the environment and acquire the flow field in the laboratory. CO_2 is a compressible fluid that is sensitive to changes in temperature and pressure [7], introducing difficulties to studies. Kim et al. [8] were the first to simulate the heat transfer of SC-CO_2 laminar impinging jet. Wang et al. [9] simulated the flow

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Nomenclature

$\vec{v}$	vector of velocity
t	time, s
p	pressure, Pa
H	specific total enthalpy, J·kg^{-1}
k_{eff}	effective thermal conductivity, W·m^{-1}·K^{-1}
T	temperature, K
k	turbulent kinetic energy
G_k, G_b	generation of turbulent kinetic energy
Y_m	contribution of the fluctuation dilatation
a	gravitational parameter
b	repulsive force parameter
P_c	critical pressure, Pa
T_c	critical temperature, K
T_r	reduced temperature
C_p	real fluid heat capacity, cal·mol^{-1}·K^{-1}
C_p^*	ideal fluid heat capacity, cal·mol^{-1}·K^{-1}
ΔC_p	deviation heat capacity, cal·mol^{-1}·K^{-1}
M	molecular weight
Z_c	critical compression factor

Greek

ρ	density, kg·m^{-3}
$\overline{\overline{\tau}}$	stress tensor
ε	turbulent dissipation rate
μ	gas viscosity under high pressure, Pa·s
μ_0	gas viscosity under low pressure, Pa·s
ρ_r	reduced density
λ	thermal conductivity coefficient under high pressure, W·m^{-1}·K^{-1}
λ_0	thermal conductivity coefficient under low pressure at a temperature of 0 °C, W·m^{-1}·K^{-1}

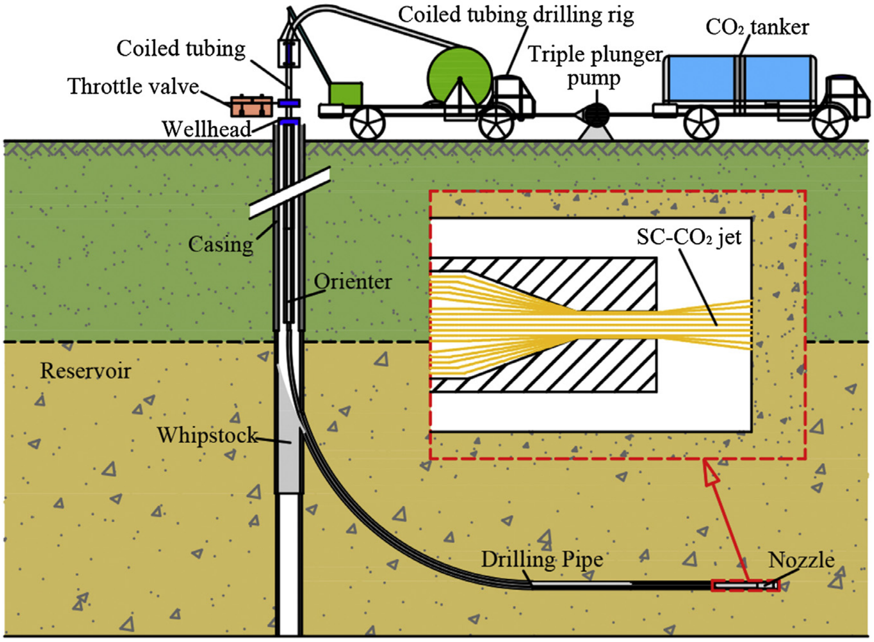

Fig. 1. Schematic drawing of coiled tubing drilling with SC-CO_2 according to Ref. [4].

field of SC-CO_2 jet using CFD method. They considered the thermal conductivity and compressibility of CO_2, but they did not define the changes in physical parameters with pressure and temperature for high-speed flow.

A CFD simulation model developed by Shen et al. [10] can be used to study the flow characteristics of SC-CO_2. They used this model to study the low-velocity flow of SC-CO_2 in a borehole, and cutting–carrying laws at different viscosities and densities were acquired. The calculation models used by He [11] and Guillaument [12] are both suitable for the low-velocity flow of SC-CO_2 in a mini tube. In the cited models, changes in the temperature and pressure which could result in changes in the physical properties were considered. However, the SC-CO_2 jet used to break rocks at well bottom flows at high speed, and it is different from the cited pipe flow, which is of low velocity and undergoes small pressure changes.

Cheng [13] established a numerical method to simulate the free flow field of SC-CO_2 jet, while Liu [14] established a model to study the rapid expansion of SC-CO_2 and Cardoso [15] conducted CFD analysis of a supercritical antisolvent. They all took the changes of CO_2 physical properties into account. The SC-CO_2 flows in the cited studies have in common a free flow field after the injection. SC-CO_2 jet at well bottom impacts on rocks after it is injected by the nozzle. The CO_2 fluid goes through two radical changes in pressure and temperature. One occurs after injection from the nozzle, while the other occurs during the impact on rocks. It is thus not suitable to apply the cited models to simulate SC-CO_2 impacting jet.

The present work is aimed to develop a numerical model for the simulation of the real flow field of SC-CO_2 impacting jet at well bottom. The structure of the flow field can be analyzed from the simulation results. Additionally, similar simulation experiments of SC-CO_2 impacting jet were conducted in the laboratory. Sensors were used to measure the pressure and temperature on a wall and to thus verify the simulation results.