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Particle velocity distributions of abrasive liquid nitrogen jet and parametric sensitivity analysis

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A R T I C L E I N F O

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A B S T R A C T

To identify the velocity distributions of abrasive particles in abrasive liquid nitrogen jet, a computational fluid dynamic model was built to simulate the flow field of abrasive liquid nitrogen jet. The velocity of particles in liquid nitrogen jet was solved using the Lagrangian discrete phase model by coupling the physical property equations of nitrogen and then compared with that in water jet. Additionally, a parametric sensitivity analysis was performed to study the effect of both abrasive particle and jet parameters on particles velocity distributions in liquid nitrogen jet. The results showed that the high pressure liquid nitrogen which carried abrasive particles could generate high speed abrasive liquid nitrogen jet under the acceleration action of jet nozzle. Given the same pressure drop of nozzle, the maximum velocity of particle in liquid nitrogen jet was about 8.04% higher than that in water jet. With regard to abrasive particle parameters, the velocity of particles in liquid nitrogen jet decreased with the growth of the particle diameter and mass flow rate while was slightly affected by particle initial velocity. For jet parameters, the velocity of particles increased with the growth of nozzle pressure drop, nozzle diameter and fluid temperature, but was hardly influenced by confining pressure. This study is expected to provide theoretical references for design and application of abrasive liquid nitrogen jet.

1. Introduction

With the rapid development of fracturing technology, liquid nitrogen had been successfully used as a fracturing fluid in 1990s (Mcdaniel et al., 1997; Grundmann et al., 1998). Because of its extremely cryogenic temperature (−195.8 °C), liquid nitrogen can induce thermal fractures on the rock during fracturing process (Ren et al., 2013; Cai et al., 2014). Liquid nitrogen is colorless, tasteless and hardly reacts with other formation fluids. Thus, it can not only avoid reservoir damage but also fundamentally solves the issues of water consumption and pollution.

Currently, some fundamental researches on liquid nitrogen fracturing have been performed. Mcdaniel et al. (1997) conducted a laboratory test to observe the cracking effect of liquid nitrogen cooling on coal samples. They found that when the coal samples were submerged in liquid nitrogen, they breaked into smaller cubical units. Grundmann et al. (1998) analyzed the thermal stresses generated by cryogenic cooling during liquid nitrogen fracturing and indicated that the thermal induced fractures orthogonal to the main fracture plane were expected to be produced. Ren et al. (2013) established a stress–strain analysis model and conducted the ultrasonic tests to research the cracking effect of liquid nitrogen on coal. The results showed that additional stress could be produced inside coal matrix, thereby causing the expansion of micro-fractures. Cha et al. (2014) designed the experimental setups and performed laboratory tests to study the feasibility of fracturing stimulation with liquid nitrogen. The experimental results showed that thermal fractures were created due to the liquid nitrogen rapid cooling and the generation of fractures was influenced by the rock properties. Although the researches above have proved that the liquid nitrogen can aid in rock cracking, fracturing stimulation with liquid nitrogen still has some technical issues.

As the conventional isolation devices (e.g. packer and bridge plug) used in multistage fracturing are hard to work efficiently under extremely cold condition, conventional liquid nitrogen fracturing usually fails to control the fracture initiation locations and isolate the wellbore sections. When the first-stage fracturing

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treatment is completed, 0.5~0.8 m^3 water will be injected to seal fractures, which is called “frozen water” diverter in this technology (Mcdaniel et al., 1997). In the subsequent fracturing procedure, fractures could only be initiated above the “frozen water” zone. In this case, it is impossible to realize the multistage fracturing effectively. Thus, efficient multistage fracturing treatment with liquid nitrogen must be identified.

Hydrajet fracturing (HJF) technique is a multistage fracturing method which integrates abrasive jet perforating, hydraulic fracturing and hydrodynamic sealing (Surjaatmadja et al., 1998; Li et al., 2010; Sheng et al., 2013). During HJF, the casing and formation are penetrated with abrasive jet, thereby forming a perforation cavity as shown in Fig. 1 (Li et al., 2009). Then the formation can be cracked at the jetting locations accurately according to pressure boosting effect during hydrajet fracturing (Qu et al., 2010). Thus, fracturing with liquid nitrogen jet (i.e. liquid nitrogen jet fracturing) is expected to overcome shortcomings of conventional treatment, especially the difficulty in fracture location control and wellbore isolation. For liquid nitrogen jet fracturing, the first treatment is to create perforation cavity utilizing abrasive liquid nitrogen jet. The key of perforation with abrasive jet is that whether the high speed jet can accelerate abrasive particles to high velocity to impact the steel casing, cement and formation rock (Niu et al., 2003).

To identify the acceleration effect of liquid nitrogen jet on particles, a computational fluid mechanics (CFD) model was established. The flow field of abrasive liquid nitrogen jet and the particles velocity distributions were simulated using Discrete Phase Model (DPM) (Wang, 2004). Finally, effect of abrasive particle parameters (particle diameter, initial velocity and mass flow rate) and jet parameters (nozzle pressure drop, nozzle diameter, fluid temperature and confining pressure) on velocity distributions of particles was analyzed. The simulation results verified the acceleration effect of liquid nitrogen jet on particles and provided theoretical references for the application of both abrasive liquid nitrogen jet and liquid nitrogen jet fracturing.

2. CFD model

2.1. Geometric model and boundary conditions

Fig. 2 is a two-dimensional geometry model of flow domain of abrasive liquid nitrogen jet. It was mainly composed of two regions: the internal space of nozzle and jet region (between the nozzle outlet and impact wall). The nozzle with an axial symmetry structure mainly consisted of conical section and cylinder section. Their lengths were three and two times as long as nozzle outlet diameter respectively. In Cartesian coordinate system, the center of the nozzle outlet was set as the origin. The high pressure liquid nitrogen entered the flow domain from nozzle inlet and then flowed out after impacting the right wall. In this model, the nozzle inlet was set as the pressure -inlet boundary and the outlet of jet region was set as the pressure-outlet. Other walls were set as the non-slipping wall boundaries.

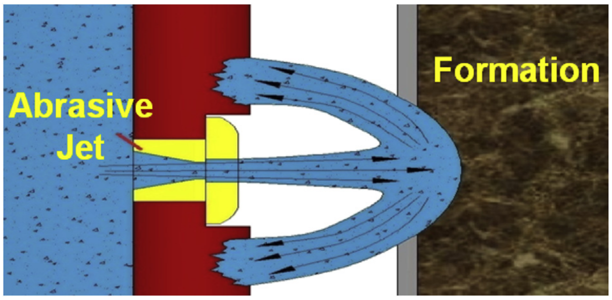

Fig. 1. Schematic diagram of perforation with abrasive jet.

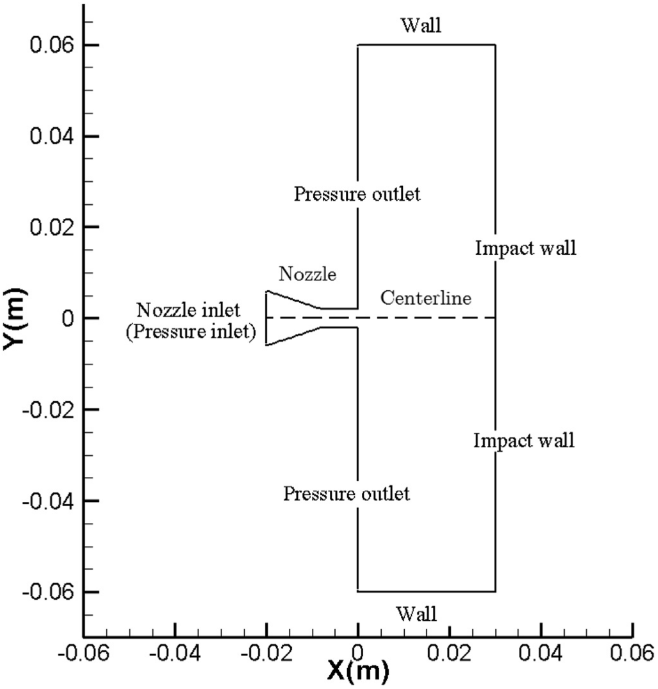

Fig. 2. Geometry model of flow domain.

2.2. Mathematical model

Abrasive liquid nitrogen jet involves heat transfer, compressible flow and multiphase flow. Mass equation, momentum equation, energy equation and multiphase flow equation are needed to be solved. Because the volume fraction of particles in abrasive jet is generally less than 10%, the Lagrangian DPM in Fluent is adopted to simulate the flow field and the particles velocity distributions. In DPM, the fluid phase is solved by Navier–Stokes equations while the discrete phase is solved by tracking a large number of particles. The particles can exchange momentum, mass, and energy with the fluid phase, but the interaction between particle and particle is neglected (Wang, 2004). The standard k-ε model was used to solve the turbulent flow field caused by the strong shearing effect of high speed jet. On the compute nodes of flow domain, the properties of nitrogen were controlled by temperature and pressure. On the other hand, the change in nitrogen properties influenced the flow field in turn. Hence, it is necessary to consider the nitrogen properties.

Total four properties were involved in the flow field simulation of abrasive liquid nitrogen jet. They were density, isobaric heat capacity, viscosity and thermal conductivity. Density and isobaric heat capacity of nitrogen were calculated by Span et al. model (Span et al., 2000). As shown in Eq. (1), this equation is the function of two independent variables: reduced density (δ) and inverse reduced temperature (τ).

$$\alpha(\delta,\tau) = a(\rho,T)/(RT) \tag{1}$$

where $a(\rho,T)$ is the Helmholtz energy; $\alpha(\delta,\tau)$ is reduced Helmholtz energy; R is the gas constant, equal to 0.2968 kJ/(kg·K); δ and τ are two independent variables, $\delta = \rho/\rho_c$ and $\tau = T_c/T$; ρ and ρ_c are density and critical density of fluid, kg/m^3; T and T_c are temperature and critical temperature, K. For nitrogen, ρ_c is 313.30 kg/m^3 and T_c is 126.192 K.