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Paper

EXPERIMENT ON SUPERCRITICAL CO_2 ABRASIVE JET PERFORATION

Wang Haizhu[a]*, Li Gensheng[a], He Zhenguo[b], Tian Shouceng[a], Wang Meng[a], Wang Youwen[a]
[a] *Associate Professor, China University of Petroleum, Beijing, China*
[a] *Professor, China University of Petroleum, Beijing, China*
[b]*Engineer, China Research Institute of Petroleum Exploration & Development (CNPC), Beijing, China*
[a] *Associate Professor, China University of Petroleum, Beijing, China*
[a] *Undergraduate Student, China University of Petroleum, Beijing, China*
[a] *Undergraduate Student, China University of Petroleum, Beijing, China*
**Corresponding Author's E-mail*: whz0001@126.com

ABSTRACT

Supercritical CO_2 jet fracturing is usually regarded as one of the most effecient methods to exploit unconventional oil&gas. Casing and formation perforation plays a great role in the procedure of jetting fracturing. The properties of supercritical CO_2 fluid such as density and viscosity change greatly with the variation of temperature and pressure, which directly affect the particle-carrying ability and perforation performance. This paper investigates the influence of parameters such as ambinent pressure, fluid temperature, jet standoff distance and jet pressure on the perforation ability of abrasive supercritical CO_2 jet. As the experimental results indicate, under the condition of a fixed jet differential pressure, the ambinet pressure has no significant effect on perforation. Hole depths and diameters decrease 5.7% and 18.6%, respectively. When the jet temperature rises, the hole depths increase slightly. In addition,with the jet temperature rising per 20℃ within the range from 40 to 100℃ and the standoff distances being 4mm and 10mm, the hole depths increase by 3.8 percent and 12 percent in average, respectively. With the increase of the standoff distance, the hole depths firstly keep unchanged and then decrease rapidly. However, the hole diameters and effectively impinged areas increase with the standoff distance. The jet pressure has a similar influence on the perforation performace as well as the conventional jet. With the increase of the jet pressure, both effective hole depths and volumes increase linearly in general. The hole depths averagely increase by 36.6 percent with the jet pressure rising by 5MPa. The perforation performance of pre-mixed jet is better than the post-mixed jet. Under these experimental conditions, both of the hole volume ratio is 12.02. All the above results provide a theoretical foundation for the implementation of supercritical CO_2 jet fracturing technology.

Keywords: Supercritical CO_2, Abrasive jet, Perforation, Experiment, Fracturing.

1 INTRODUCTION

In the recent decades, the United States has successfully exploited shale oil and gas and promoted the global shale revolution with the technology of large-scale hydraulic fracturing. Shale gas resources in our country are abundant but have poor reservoir properties, almost existing in arid, mountainous and densely populated areas. The large-scale hydraulic fracturing has brought a huge pressure to the water resources, as well as the reservoir, underground water and ground environment pollution. Therefore, we have to find more suitable and efficient fracturing fluids and methods.

Supercritical CO_2 has characteristics of low viscosity and high diffusivity close to those of gas and high density close to that of liquid. Besides, its surface tension is zero[1-2]. Researches at home and abroad have indicated that it is able to avoid the clay swelling in shale reservoir to use the supercritical CO_2 as the fracturing fluid. In addition, it is pollution-free to the underground and surface environment, which poses no pressure on water resource. For these reasons, supercritical CO_2 fracturing is considered as an efficient way to exploit the shale reservoirs [3-4].

Recently, the hydrojet fracturing technology which is famous for its high efficiency and low cost has got a rapid development [5,6]. It is expected to achieve a better effect [7] to combine the supercritical CO_2 with the hydrojet fracturing to conduct supercritical CO_2 jet fracturing. In 1998, J.J.Kolle et al. in America put forward an application of supercritical CO_2 jet into rock-breaking and drilling. The jet rock-breaking experiments were carried out on shale and granite in 2000, which had confirmed the rock-breaking characteristics of high efficiency and low threshold pressure with the supercritical CO_2 jet [8]. In 2012, Du et al. conducted experiments on main factors that affected rock-breaking of supercritical CO_2 jet, and had further validated the characteristics of high efficient rock-breaking with supercritical CO_2 jet [9]. That same year, Wang et al got laws of main parameters such as jet standoff distance, jet pressure, and jet temperature affecting the rock-breaking performance with the supercritical CO_2 jet with laboratory experiments [10]. However, it is difficult to perforate the casing with the pure supercritical CO_2 jetting method. We proposed the idea of adding particles to supercritical CO_2 jet for perforating casing window. That was essential for perforating casing and formation window in jet fracturing.

In order to reveal the characteristics of abrasive supercritical CO_2 jet perforation, laboratory experiments were carried out to obtain the sensitive laws of major parameters, such as jet standoff distance, jet pressure, fluid temperature and abrasive particle size. The results provide a theoretical foundation for the formation of supercritical CO_2 jet fracturing technology.

2 EXPERIMENTAL APPARATUS AND SCHEME

2.1 Experimental apparatus

The experiments were done with the experimental system of abrasive supercritical CO_2 jet perforation (Fig.1 is the flow chart) in high-pressure water jet laboratory in China University of Petroleum (Beijing). The system consists of storage unit of liquid CO_2, high pressure triplex pump, storage unit of supercritical CO_2, feeding set of abrasive, jet erosion body with ambient pressure, unit of miscellaneous removal and filter etc. In the experiment system, the maximum ejected pressure and simulated temperature are 100MPa and 100℃,respectively. Reactor with ambient pressure for rock-breaking can actually simulate temperature and pressure of bottom hole in different depth.

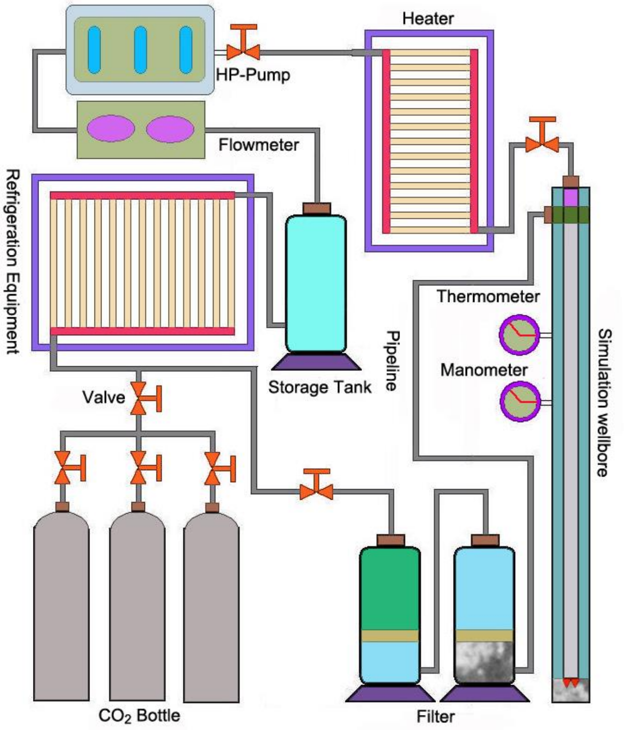

Fig. 1 The flow chart of the SC-CO_2 jet system

The abrasive feeding set (Fig. 2) is the core of the experimental system, including the abrasive tank, auger propeller, connecting pipes and so on. The auger propeller has two outlets and is connected with the jet nozzle through two guide tubes to achieve pre-mixed and post-mixed abrasive jet. The feeding speed of the abrasive is controlled by adjusting the rotatory rate of auger. The maximum pressure created by the feeding set of abrasive is 100MPa, thus the setup could achieve the ability of adding abrasive particle under high pressure condition.

Fig. 2 Abrasive feeding facility

2.2 Experiment materials

Materials used in the experiment are mainly CO_2, abrasive, perforation samples etc. Abrasive is made of the brown corundum (Fig. 5) whose density of 3.9g / cm3.

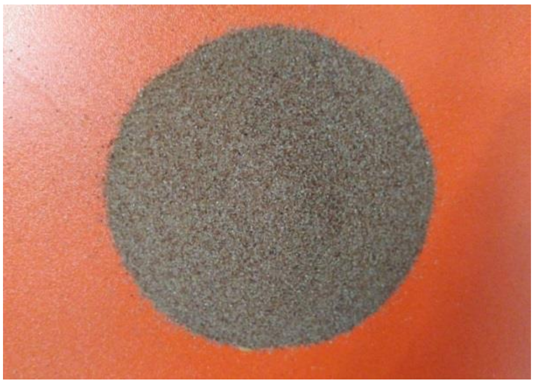

Fig. 3 Experimental abrasive (corundum)

The experimental perforation samples, whose length and diameter are 100 and 25.4mm, respectively, consist of core and metal, such as sandstone, marble, limestone, shale, and aluminum blocks (Fig.4). Rock mechanical parameters of the above samples are shown in Table 1.

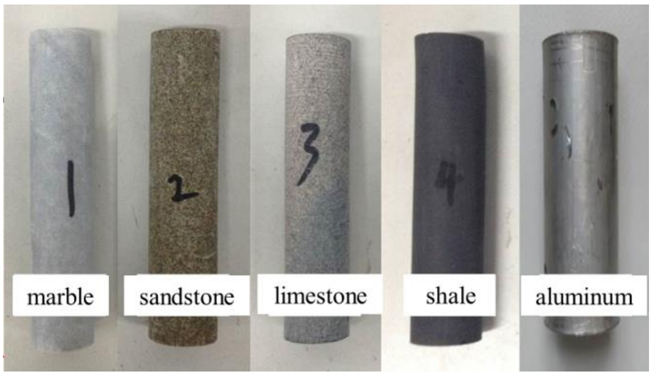

Fig. 4 Experiment samples

Table 1 Rock mechanical parameters of the experiment samples

Target material	Density g/cm^3	Elastic modulus GPa	Poisson's ratio	Compressive strength MPa	Tensile strength MPa
Sandstone	2.40	9.7	0.233	110.7	6.1
Marble	2.92	50.4	0.266	216.1	9.3
Limestone	2.64	43.8	0.215	333.1	12.7
Shale	2.59	36.5	0.190	351.4	14.4
Aluminu-m block	2.70	70.0	0.33	120.0	60

The industrial bottled CO_2 is chosen as the experimental gas (Fig.5) requiring the pressure in the bottle is kept at least above 4.5 MPa to ensure that CO_2 is filled in the tank smoothly. Then the requirement of the water in CO_2 do not need to be too much to avoid the water to enter the experimental system and combine with CO_2 producing carbonic acid that corrodes pipelines and other apparatus, or forming hydrate in pipelines that blocks flow channel causing danger, meanwhile, CO_2 is required to be of high purity to reduce the negative influences caused by other gas impurities on the rock-cutting efficiency.

Fig. 5 Liquid CO_2

2.3 Experiment schemes

The main factors affecting perforation performance of the abrasive supercritical CO_2 jet consists of the jet pressure, simulated confining pressure, fluid temperature, jet standoff distance and abrasive particle size, mixed ways of abrasive etc. Referring to the conditions of downhole temperature and pressure and using cross experiment method, the experimental schemes are as shown in table 2.

Table 2 Parameter matrix of experiments on abrasive SC-CO_2 jet perforation

The serial number	jet standoff distance（dimensionless distance ）	fluid temperature K	jet pressure differential MPa	simulation of confining pressure MPa	abrasive particle size mm	Target type
1	1~32	333	20	5/10	0.18	marble / aluminum block
2	4/10	313~373	20	5/10	0.18	marble / aluminum block
3	4/10	333	5~30	5/10	0.18	marble / aluminum block
4	4/10	333	30	5~15	0.18	marble / aluminum block
5	4/10	333	30	5/10	0.25/0.18/0.15	marble / aluminum block
6	4/10	333	30	5/10	0.18	sandstone /

	marble / limestone / shale / aluminum block

3 EXPERIMENT RESULTS AND ANALYSIS

3.1 Jet pressure

Jet pressure is one of the most important factors which affect the effect of abrasive water jet. In this experiment, the jet pressure varies from 5MPa to 25MPa, other parameters are constant. The ambient pressures are 5MPa and 15MPa, respectively. The diameter of the nozzle is 1.0mm. The dimensionless jet standoff distance is 10 and the fluid temperature is 333K. The exposure time is 3 min and ejected samples are marble. The changes of the jet perforation performance and hole depth with the variation of the jet pressure are shown in Fig.6 and Fig.7.

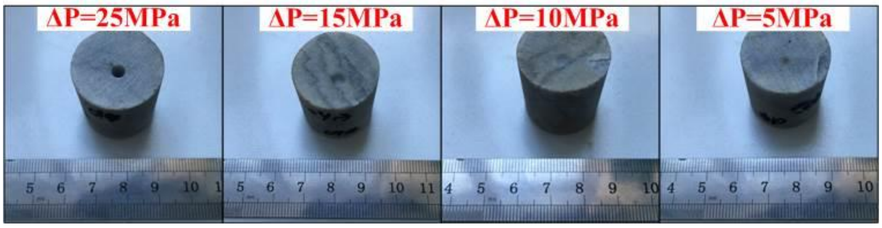

Fig. 6 Photos showing jet perforation performance versus jet pressure

As shown in Fig.7, perforation depths increase linearly with increasing jet pressure, an increment of 1.2mm in average. There are less changes in the hole diameter, averagely increasing by 0.04mm. An average increase of hole volume is about 50.5mm^3 and the growths in average are 36.6%, 1.70% and 67.8%, respectively.

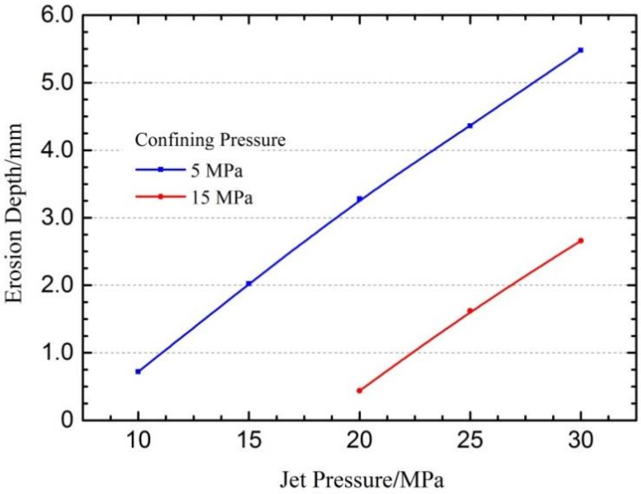

Fig.7 Influence of the jet pressure on abrasive SC-CO$_2$ jet perforation performance

3.2 Ambient pressure

Properties of the supercritical CO_2 fluid are closely related to the ambient pressure. In order to investigate the effect of the ambient pressure on the performance of abrasive jet, the experimental ambient pressure ranges from 5MPa to 15MPa. The jet pressure and pressure difference are both constant, 30 and 15MPa, respectively. Other parameters are constant. The laws of the ambient pressure affecting the perforation depth of abrasive supercritical CO_2 jet are shown in Fig.8.

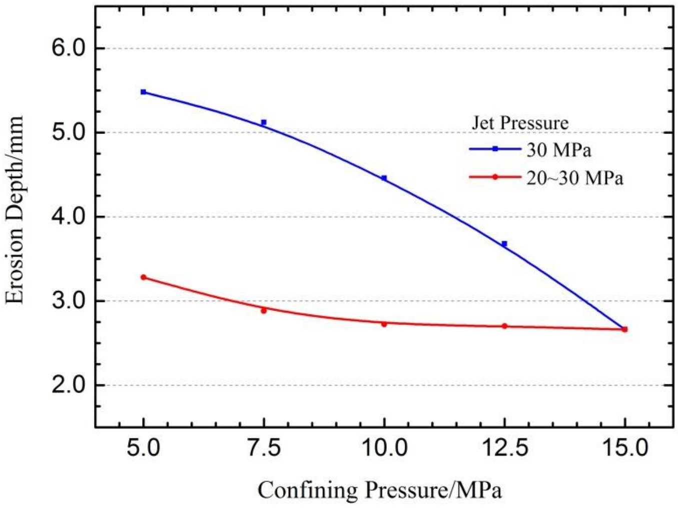

Fig. 8 Influence of the ambient pressure on abrasive SC-CO_2 jet perforation performance

As shown in Fig. 8, in the case of the constant jet pressure, the perforation hole depths decrease with the increasing ambient pressure. Under the condition of constant jet pressure, there are less changes in hole depth and no significant changes in hole diameter in the two groups of the experiments. Under a constant ejected pressure, the ambient pressure increases from 5MPa to 15MPa. The hole depths, diameters and volumes reduce by 15.7%, 2.05% and 33.5% in average, respectively. For a constant jet pressure difference, three cases reduce averagely by 5.7%, 1.86% and 18.6%. In addition, under the condition of the constant jet pressure dropout, after the ambient pressure increased from 5MPa to 7.5MPa, CO_2 outside the nozzle changes from the gas state to the supercritical state because of the increasing density. And the resistance increases after high-pressure jet ejecting through the nozzle. Therefore, when the ambient pressure changes between the upper and lower critical pressure, there are more obvious changes in the hole depth. But when the ambient pressure increases from 7.5MPa to 15MPa, CO_2 outside the nozzles is the supercritical state. The density increases gradually and hole depth changes less.

3.3 Fluid temperature

Temperature is also a unique factor which affects the properties of the supercritical CO_2 fluid. The experimental fluid temperature is controlled in the range of 313K ~ 373K. The jet pressure and simulated ambient pressure are 30MPa and 10 MPa, respectively. The jet standoff distances are 4mm and 10mm and other parameters keep constant. The variation curves of the perforation depth with the change of fluid temperature are shown in Fig. 9.

As shown in Fig. 9, the perforation depth increases with the increase of fluid temperature but the increment is limited. When the fluid temperature rises from 313K to 373K and jet standoff distance is 4mm, perforation depth increases averagely by only 3.8% with a temperature increment of every 20K. However, when the jet standoff distance is 10mm, it increases by 12.0% in average with the temperature increasing by per 20K. This is because with increasing fluid temperature the density and viscosity decrease and the jet velocity increases. Under the condition of sufficient axial length, abrasive particles can get better acceleration effect as well. Therefore the performance of perforation is enhanced.

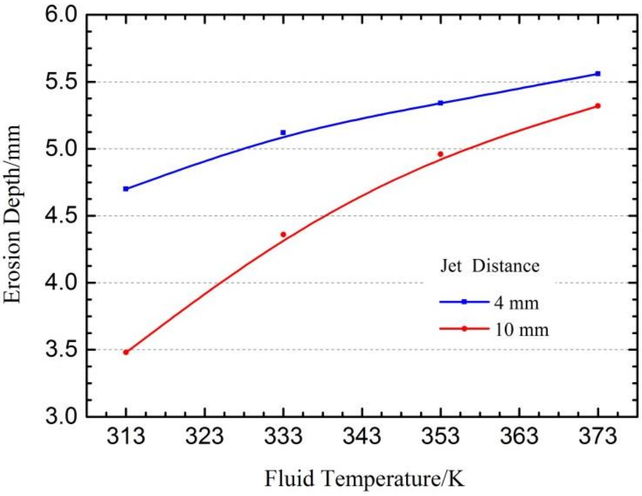

Fig.9 Influence of fluid temperature on abrasive SC-CO_2 jet perforation performance

3.4 Jet standoff distance

Jet standoff distance is the most immediate factor affecting jet perforation performance. The dimensionless jet standoff distance in experiment varies from 1 to 32. The jet pressures are 30 MPa and 15MPa, respectively. The corresponding simulated ambient pressures are 10MPa and 5MPa and other parameters keep unchanged. Fig.10 shows the curve reflecting the influence of jet standoff distance on abrasive supercritical CO_2 jet perforation performance.

As shown in Fig.10, with the increase of the jet standoff distance, hole depths firstly keep unchanged and then decrease. However, the hole diameters increase with the increase of jet standoff distance and hole volumes firstly increase and then decrease (there exists a maximum value, that is the most optimum jet standoff distance).In two groups of the experiments, as jet standoff distance increases from 1mm to 4mm, hole depths reduce respectively by 3.2% and 4.7% and the hole diameters increase by 7.02% and 9.21%, respectively. While jet distance increases from 4mm to 10mm, hole depths of two groups of experiment reduce by 17.9% and 10.7% and hole diameters increase respectively 30.43% and 40.26%. In addition, when the jet distance increases from 10mm to 20mm, hole depths decrease by 41.58% and 28.9%,respectively, and the hole diameters increase respectively by 53.66% and 44.91%. After the jet standoff distance increases to 32mm, the boundary of impinged area is indistinct, and impinged areas increase by 47.22% and 27.16%, respectively. The data is shown in table 3.

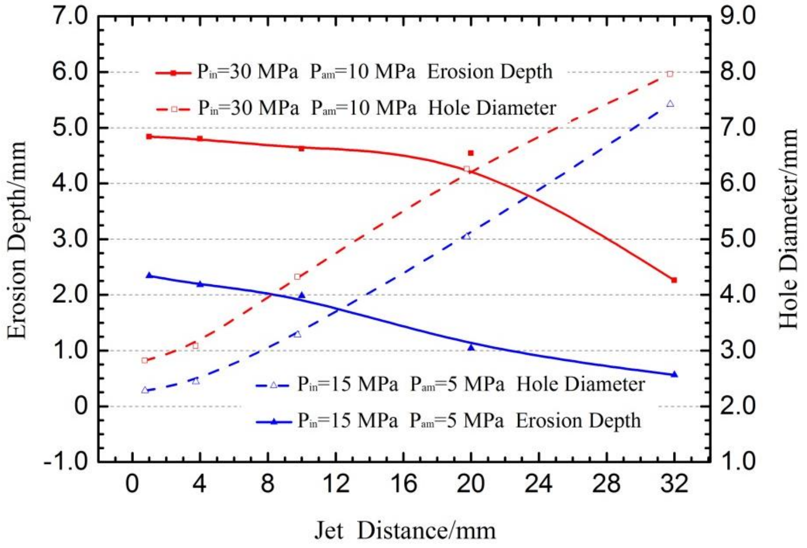

Fig. 10 Influence of jet standoff distance on abrasive SC-CO_2 jet perforation performance

Table 3 the experiment results

	increases (jet standoff distance 1~4mm)	increases (jet standoff distance 4~10mm)	increases (jet standoff distance 10~20mm)	increases (jet standoff distance 20~32mm)
Depth 1	-3.2%	-17.9%	-41.58%	-
Diameter 1	7.02%	30.43%	53.66%	47.22%
Depth 2	-4.7%	-10.7%	-28.9%	-
Diameter 2	9.21%	40.26%	44.91%	27.16%

The reason is that when the jet standoff distance changes within a narrow range, the impact velocity of abrasive is almost constant. Therefore, the rock-cutting efficiency remains unchanged and the perforation hole depth is almost constant under the same condition. With the jet standoff distance increasing, the hole diameter gradually increase, which is attribute to the increase of impinged area caused by gradual diffuse jet with increasing jet standoff distance. Thus, within the range from abrasive ejecting out the nozzle to abrasive velocity remaining unchanged, increasing jet standoff distance appropriately can improve the jet perforation efficiency.

3.5 Abrasive particle size

In the experiment, selections of abrasive diameters were 60 meshes, 80 meshes and 100 meshes, respectively. The fluid temperatures are 333K and 373K, respectively, and the jet pressure and simulated ambient pressure are respectively 30MPa and 10MPa. Other experimental conditions are constant. Influence of particle size on abrasive supercritical CO_2 jet perforation performance is shown in Fig.11.

As shown in Fig.11, the hole depths decrease with the decreasing abrasive particle size but change less. When the abrasive particle diameters reduce from 60 meshes to 100 meshes, fluid temperatures are respectively 333K and 373K, hole depths reduce accordingly by 7.63 percent and 14.81 percent. The reason is that under this experimental condition, the abrasive particles which were fully accelerated can obtain the maximum ejected velocity (as well as fluid velocity).Therefore, the larger the diameters of particles are, the larger impact force on samples is, leading to much better perforation performance. In a real operation, we should accord to different jet tools and fluid temperature environment when choosing an appropriate abrasive particle size.

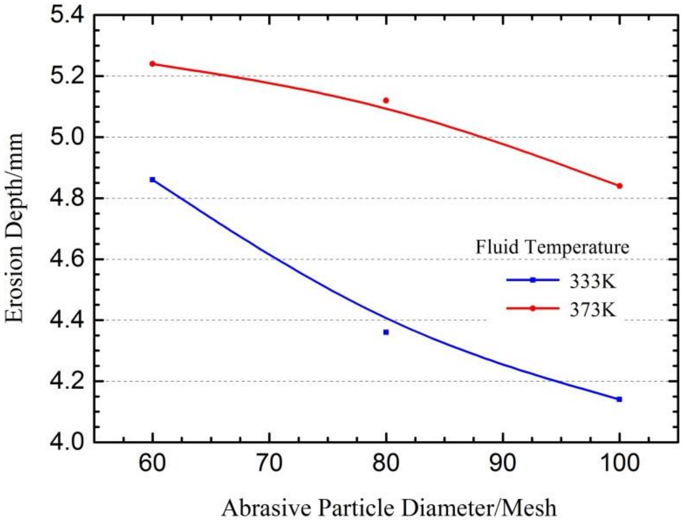

Fig. 11 Influence of particle size on abrasive SC-CO_2 jet perforation performance

3.6 Blending abrasive ways

Under the same experimental conditions, the contrast experiment is carried out on the perforation performance of pre-mixed and post-mixed abrasive supercritical CO_2 jet. The varied curve of the perforation performance with the change of jet pressure is shown in Fig. 11.

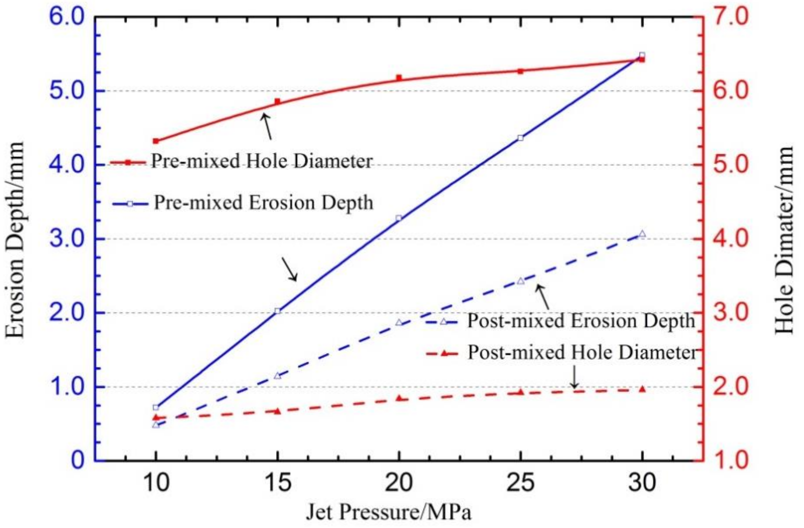

Fig. 12 Comparison between pre- and post-mixed abrasive SC-CO_2 jet perforation

As shown in Fig.12, under the same experimental conditions, the perforation performance of pre-mixed and post-mixed abrasive supercritical CO_2 jet changes similarly with the variation of jet pressure. The hole depth changes largely and the hole diameters remain unchanged. However, the perforation performance of the post-mixed jet is obviously weaker than that of the pre-mixed jet. Under the conditions of our research, the maximum ratio of perforation depth, diameter and volume of pre-mixed and post-mixed abrasive supercritical CO_2 jet are 1.76, 3.36 and 12.02, respectively.

The reason is that the particles of pre-mixed abrasive jet are mixed more evenly, and accelerated more fully, while the particles in post-mixed abrasive jet nozzle are not able to be accelerated fully, thus weakening the perforation ability. In the premise of rational designing jet pressure and avoiding nozzle abrasion, the pre-mixed abrasive supercritical CO_2 jet can be applied into perforation operations.

4 CONCLUSIONS

(1) Abrasive supercritical CO_2 jet can erode all samples that are made of rock and aluminum to the holes which have similar morphology, demonstrating abrasive supercritical CO_2 jet perforation can be carried out industrially.

(2) Similar to the water jet, the jet pressure and standoff distance have notably influence on the perforation effect of abrasive supercritical CO_2 jet. The perforation effect achieves enhancement with the increase of jet pressure. With the increase of jet standoff distance, the hole depths firstly keep unchanged and then decrease rapidly. For the perforation efficiency, there exists an optimum value of jet standoff distance.

(3) Dramatic changes take place in the fluid properties with the phase change of CO_2, which causes notably influence on the perforation performance. However, CO_2 is in the supercritical state and fluid characteristics change continuously, the perforation effect changes gently in general.

(4) With the fluid temperature rising, the jet velocity gradually increases and abrasive jet velocity heightens, causing enhancement of the perforation effect.

(5) Under these experimental conditions, all kinds of abrasive particle diameter can achieve the maximum velocity which is equivalent to supercritical CO_2 jet; with the diameter of abrasive particle increasing, the impact force of abrasive exerted on the samples increases and the perforation effect is strengthened.

Both pre-mixed and post-mixed abrasive supercritical CO_2 jet perforation have the same varied laws with changing jet pressure, but the perforation performance of pre-mixed abrasive jet is better than that of the post-perforation abrasive jet.

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