INTRODUCTION

Down-the-hole (DTH) air hammer drilling is considered as one of the most efficient drilling methods for hard rock drilling. In the DTH air hammer drilling, straighter holes and low costs per metre are achieved by the frequently percussion action and high impact loads at the bit inserts. Contacting time of drill bit inserts with the rock formations is typically about 2% of the total operational time, resulting in a higher instantaneous weight-on-bit (WOB), even though the mean...
WOB is maintained at a lower level.\textsuperscript{6-8} It has also shown potential for seismic-while-drilling (SWD) purposes and characterizing drilling conditions.\textsuperscript{9,10} In addition to these, compared to the conventional mud drilling methods, using air as the circulation fluid results in higher rate of penetration (ROP) because of the low annulus bottom hole pressures.\textsuperscript{11} Furthermore, drilling of potential producing formations using annulus bottom hole pressures that are below the formation pore pressure can eliminate formation damage that could affect follow-on production.\textsuperscript{11} Due to the aforementioned advantages, DTH air hammer drilling has been used widely in mining and has also expanded to oil and gas drilling operations since more and more oil and gas reservoirs are under hard rock formations.

Reverse circulation down-the-hole (RC-DTH) air hammer is an innovative DTH hammer drilling tool driven by air.\textsuperscript{12} Different from the conventional DTH air hammer system, the drill bit with specially designed structure is the key parts of the RC-DTH air hammer system, and the dual-wall drill pipes build the transport passages for both the compressed air and drill cuttings.\textsuperscript{13} During drilling, compressed air is injected into the annulus of the dual-wall pipes and drives the RC-DTH air hammer to implement high-frequency blows acting on a reverse circulation (RC) drill bit where the reverse circulation is formed.\textsuperscript{14} A striking feature of this drilling method is the combination of percussion drilling with the air RC drilling technique.

Conventionally, in an air direct circulation drilling, compressed air is inputted into the borehole bottom through the center passage of drill pipes, then the exhaust air brings the drill cuttings out of the borehole through the annulus space formed by drill pipes and hole wall.\textsuperscript{15} Whereas, in an air RC drilling, the compressed air enters the annulus space of the dual-wall drill pipes via the dual-wall swivel; the exhaust air carrying the drill cuttings returns to the surface through the center passage of the inner drill pipes instead of the annulus space formed by the outer drill pipe and the borehole wall. As shown in Figure 1, the cross section area of the center passage (yellow circle $b$) of the air RC drilling system is much smaller than that of the annulus cross section area (green annulus $a$). According to the minimum volume requirement for air drilling, it is convinced that the minimum travelling velocity of air (standard condition) is about 15.2 m/s for satisfying the transport of drill cuttings. The studied conducted by Sharma and Chowdhry\textsuperscript{16} also indicated that only keeping the air with a reasonable travelling velocity can transport the drill cuttings efficiently. The air RC drilling is obviously much easier to reach the threshold travelling velocity as the air carrying drill cuttings flows in the center passage rather than the annulus space between drilling pile and borehole wall.\textsuperscript{17-20} Therefore, low air consumption and the consequent capability in large-diameter-hole drilling is a distinct advantage for the air RC drilling, which significantly reduces the reaming cost and operation time. Additionally, as the air and drilling cuttings exhausted from the discharge pipe can be guided directly into the cuttings and dust collector unit placed far from the drill site, the operating environment is improved and the atmosphere is oil-free, thus hindering the drill workers and equipment from the threat of drilling dust.\textsuperscript{14,21}

In the RC-DTH air hammer drilling system, the RC drill bit is the key part to form the air reverse circulation. Most previous efforts on RC-DTH air hammer drilling focused on the performance of reverse circulation drill bits aimed at obtaining a better design to enhance the capability of reverse circulation. Represent efforts include a RC drill bit with suction nozzles set on the ribs; dust control performance of a RC drill bit investigated by Luo et al; performance analysis of a RC drill bit with a swirling generator; and the RC drill bit with multi-supersonic nozzles.\textsuperscript{14,20,22,23} The diameters of these RC drill bits studied in these previous work were ranging from 80 to 200 mm. The application potential evaluation and performance analysis of the RC drill bits with large-diameter (more than 300 mm) remain primarily unexplored. In order to improve the RC ability of the drill bit with large-diameter, the effects of suction nozzle parameters on the performance of the drill bit were studied computationally and a field trial was conducted to validate its feasibility.
2 | DESCRIPTION OF THE RC DRILL BIT

Figure 2 shows the schematic structure of the RC drill bit. The compressed air flows into the center passage of the drill tool through the suction nozzles and the flushing nozzles. The air enters the suction nozzles, where it forms jets with high flow velocity; some air adjacent will be entrained into the jets due to the jet-pump effect, resulting in a negative pressure zone in a vicinity of the jets. This pressure difference between the borehole bottom and the negative pressure zone inside the center passage can produce a lifting force acting on the air and drilling cuttings underneath. Meanwhile, air mixed with drill cuttings are sucked into the center passage of the drill tool continuously with the help of the jet flows issuing from flushing nozzles, which sweep drill cuttings into the center passage. This suction ability is of critical importance for evaluating the performance of a RC drill bit, and can be represented by the ratio between the mass flow rate of air entrained into the annulus space between the drill pipes and borehole wall and the total input mass flow rate.

3 | COMPUTATIONAL SIMULATION APPROACH

3.1 | Computational domain and grid

The reverse circulation drill bit with an outer diameter of 665 mm were studied. This size of the drill bit matches to the RC-DTH air hammer with outer diameter of 400 mm. The computational domains were established by Altair HyperWorks software. A typical meshed computational domain is shown in Figure 3. The computational domains mainly consist of five parts, including the suction nozzles, the flushing nozzles, annulus space between inner and outer walls of the drill bit, annulus space formed by the drill bit and borehole wall, and center passage of the drill tool. All the computational domains were meshed with tetrahedral unstructured grids due to the complex geometry of the domains. Three densities of grid cells were employed to analysis the grid sensitivity of the drill bit models. The results in Table 1 show that the maximum difference is <5%. The medium grids were used in our computations to balance the time cost and the model accuracy.

3.2 | Governing equations and boundary conditions

The internal air flows are considered to follow the principles of conservation of mass, momentum and energy. The general governing equation is [24]:

$$\frac{\partial (\rho \phi)}{\partial t} + \text{div} (\rho u \phi) = \text{div} (\Gamma \text{grad} \phi) + S$$

(1)

where $\phi$ denotes the dependent variable, $u$ denotes the velocity vector, $\Gamma$ denotes the diffusion coefficient, and $S$ is the general source term.

As shown in Figure 3, the air inlet is defined as Mass_flow_inlet boundary condition. The volume flow rate of the RC-DTH
The continuity and momentum conservation equations and energy conservation equation were solved using the Ansys Fluent. Navier-Stokes equations for compressible flows along with appropriate turbulence models were adopted for internal air flow prediction. Flow simulation was carried out using a 3D density-based solver. In this approach, the governing Navier-Stokes equations are solved sequentially using iterative methods until defined values meet the convergence. To deal with the coupling of velocity and pressure, the semi-implicit pressure linked equations (SIMPLE) algorithm scheme, which links the continuity and momentum equations to an equation for pressure, was adopted due to the considerable accuracy and easy to meet the convergence. Besides, the standard \( k-\varepsilon \) turbulent model based on model transport equations was used. The convective terms, in terms of turbulent kinetic energy and turbulent dissipation rate were calculated by the second order upwind discretization, while the diffusion terms were solved by central difference.

### 4 SIMULATION RESULTS AND DISCUSSION

Figure 4 shows the static pressure variation on the center line of the center passage. The static pressure near the suction nozzle outlets in the jet direction is significantly lower than that of the borehole bottom. The pressure different reaches 20 kpa, posing a distinct lifting force that pumps the drill cuttings out of the borehole bottom efficiently. In order to form an effective reverse circulation, the structure of suction nozzles should be specially designed. Therefore, fourteen computational domains with different suction nozzle parameters were established and investigated. The influence of input air mass flow rate, the diameter, elevation angle and deflection angle of the suction nozzles on the reverse circulation ability of the RC drill bit were studied. Figure 5 shows a typical velocity contour of the RC drill bit. As observed, with the compressed air flowing into the center passage, several vortexes occur near the outlet of the suction nozzles and borehole bottom. The vortexes formed in the vicinity of the outlet of the suction nozzles expand the area of low pressure zone, however, these vortexes also result in a waste of kinetic energy of the jets issuing from the suction nozzles, thus weakening the entrainment effect of the jets, and inevitably hindering the drill cuttings passing through the center passage. While the vortexes driven by the jets flow out of the flushing nozzles at the borehole bottom can stir up drill cuttings and help lift them into the center passage.
4.1 Influence of input air mass flow rate on the suction ability

The input air mass flow rate is the only parameter that can be adjusted when the drill tool is manufactured. Moreover, owing to the fact that a DTH air hammer is assembled at the top of the RC drill bit, the air mass flow rate passing through the drill bit changes over time. Generally, the air mass flow rate is modified because of the piston movement of the DTH air hammer. Investigation on the effect of input air mass flow rate on the suction ability of the drill bit can provide some guidance for the drilling process. Figure 6 shows the effect of input air mass flow rate on the reverse circulation ability. In this group of simulations, some structure parameters of suction nozzles were given, including 60° elevation angle, 18 mm diameter of suction nozzles, and 15° deflection angle. Additionally, the suction nozzles are distributed symmetrically and circumferentially over the center passage wall, and the number of the suction nozzles are all six. The sucked air mass flow rate from the annulus space between the drill pipes and borehole wall increases with increasing of the input air mass flow rate, and it reaches its maximum when the input air mass flow rate is 1.205 kg/s, then the sucked air mass from the annulus formed by the drill pipes and borehole wall decreases rapidly with the increase in the input air mass flow rate. When the input air mass flow rate is <1.205 kg/s, increasing the input air mass flow rate of input air can improve the injection velocity of the air flow from the suction nozzles, which can improve the sucked air mass flow rate. Whereas, the cross sectional area of the center passage of the drill bit is limited, too much input air would cause the increasing resistance of the air flows, thereby weakening the suction ability of the drill bit. As observed, the suction ability (ratio between sucked and input air mass flow rate) decreased with increasing the input air mass flow rate. This may be attributed to the compressibility of air that more energy was consumed for the compression of air.

4.2 Influence of suction nozzle diameter on the suction ability

The input air has two passages to discharge from the annulus space of the dual-wall drill pipes, the suction nozzles and the flushing nozzles. When the inputting air mass flow rate is given, the ratio between the air mass flow rate at suction nozzles and flushing nozzles increases with the increase in the suction-nozzle diameters. The suction ability of the RC drill bit will increase when the jetting velocity was maintained at a certain level. Figure 7 shows the effect of suction nozzle diameter on the reverse circulation ability. In this group of simulations, some structure parameters of suction nozzles were given, including 60° elevation angle, 15° deflection angle, and input air mass flow rate 70 m³/min. When the diameter of suction nozzles is <20 mm, increasing the suction nozzle diameter benefits enhancing the suction ability of the drill bit. When the diameter is larger than 20 mm, the suction ability of the drill bit is weakened significantly. The momentum of air jets issuing from the suction nozzles exhibits dominant effect on the reverse circulation ability of the drill bit. When the diameter of suction nozzles is larger than 20 mm, the decreasing amplitude of the jet velocity prevails over the increasing amplitude of mass flow rate at the suction nozzles, thereby weakening the suction ability of the drill bit.
4.3  Influence of suction nozzle elevation angle on the suction ability

The suction nozzle elevation angle is defined as the angle between the cross section of the center passage and the center line of the suction nozzle. Figure 8 indicates that increasing the elevation angle can improve the reverse circulation ability of the drill bit. The jet flows from the suction nozzles would interfere with each other for all the suction nozzles tilted in the wall of the drill bit. These collisions among the jets would result in the energy consumption and decrease the axial momentum of the jet flows, thus impairing the reverse circulation ability of drill bit. The interference among the jet flows is more intensive when the elevation angle of suction nozzles is smaller.

4.4  Effect of suction nozzle deflection angle on the reverse circulation ability

Deflection angle of the suction nozzles represents the angle between projection of the center line of one suction nozzle on the cross section of the center passage and the normal direction of center passage wall at the outlet of the suction nozzle. Figure 9 shows the influence of suction nozzle deflection angle on the suction ability, with the increase in the deflection angle of the suction nozzles, the suction ability of the drill bit enhances significantly. Air flows from suction nozzles with a deflection angle can form swirling flows in the center passage, which improves the suction ability of the drill bit. Moreover, the deflected jets can suppress the interference among them. However, the maximum value for the deflection angle is limited by the drill bit diameter and cannot be increased infinitely.

5  FIELD TRIAL

In order to verify the penetration rate by using RC-DTH air hammer in the hard rock formation, the drill bit with outer diameter of 665 mm, and the RC-DTH air hammer with outer diameter of 400 mm (RC-DTH 400) were manufactured. Simulation results show that the optimum values of suction-nozzle parameters for the RC drill bit with outer diameter of 665 mm including suction nozzle diameter, elevation angle, and deflection angle, were 20 mm, 60°, and 20°, respectively. Nevertheless, the overlarge suction nozzle parameter would weaken the drill bit strength. The six suction nozzles with diameter of 18 mm, elevation angle of 45°, and deflection angle of 10° were ultimately selected to ensure the service life of the drill bit. The design structure of the RC-DTH air hammer and the photographic image of the manufactured prototype of the RC-DTH air hammer tool are shown in Figure 10. When the RC-DTH air hammer is working, the movement of the piston can be divided into two phases: the backhaul phase and the stroke phase, and each phase experiences air intake, air expansion, air compression, and air exhaust stages. The nominal air pressure and nominal air volume flow rate of the RC-DTH400 are 1.8 MPa and 92 m³/min, respectively; the nominal impacting frequency and impacting velocity of the piston are 14.35 Hz and 8.01 m/s, respectively. Other accessory components including dual-wall drill pipes with outer diameter of 140 mm, dual-wall kelly, dual-wall swivel were also manufactured.

The field trial site is located in Foshan, Guangdong, China. The formation of the test site consists of loose soil with thickness of 3.99 m, weathered argillaceous siltstone with thickness of 17 m, and unweathered red argillaceous siltstone under the weathered argillaceous siltstone. The loose soil layer and the weathered argillaceous siltstone layer are easily drilled by using the conventional rotary drilling
method. However, the penetration rate of drilling in the unweathered red argillaceous siltstone is relatively low, <2 m/h can be reached. And the sinking slag is difficult to clean.

In order to carry out the RC-DTH air hammer drilling test, the loose soil layer and the weathered argillaceous siltstone layer are drilled by conventional rotary drilling method. Then the RC-DTH air hammer drilling system were employed to drill the unweathered red argillaceous siltstone formation. The layout of the field test system is shown in Figure 11. One air compressor made by Atlas Copco with maximum air volume flow of 34 m³/min and nominal air pressure of 30 bar, and an air compressor made by Ingersoll Rand with maximum air volume flow of 25.5 m³/min and nominal air pressure of 24 bar, were employed to provide compressed air. A lubricator were employed to lubricate the piston. The rotary drilling rig SD20E made by Guangxi Liugong Group Co., Ltd. were employed to provide the rotary force and WOB in the drilling process.

Two test boreholes were drilled, and the maximum depth of the borehole is 50.8 m. The maximum penetration rate of 6.0 m/h were observed in the drilling process, and the average penetration rate is 4.5 m/h in the condition of air volume flow rate and air pressure below the nominal values. Field tests showed that the RC drill bit can reach a good reverse circulation condition even though the suction nozzle parameters were not the optimum. There was no sinking slag found in the borehole flushing process. As shown in Figure 12, there was little air and dust escaped from the annulus space of the drill tool and borehole wall. Drill cuttings returned to the surface are mostly middle to large sized particles. Moreover, no sinking slag found in the borehole flushing process, and the drill cuttings can continuously return to the surface. It can be concluded

**FIGURE 9** Influence of the suction nozzle deflection angle on the drill bit reverse circulation capacity

**FIGURE 10** Design structure and photographic image of the reverse circulation down-the-hole air hammer tool
FIGURE 11 Layout of the field test system

FIGURE 12 Photographic images of the field trial. A, reverse circulation formed in the drilling process; B, drilling cuttings; C, borehole flushing process; D, mouth of the discharge pipe with sprayed flows
that the RC-DTH air hammer drilling system was in a good working condition and exhibits outstanding performance in the large-diameter borehole drilling.

6 | CONCLUSIONS

In order to improve the penetration rate and obtain environment-friendly drilling operations, the RC-DTH air hammer drilling approach was proposed to drill the upper hard formations above the potential producing reservoir formation. The RC drill bit as the key part of the RC-DTH air hammer drilling system to realize the reverse circulation, a parametric study on a RC drill bit with diameter of 665 mm was performed. Results show that the increase in the elevation angle and deflection angle of the suction nozzle can improve the reverse circulation ability of the drill bit. The reverse circulation ability of the drill bit reaches its maximum when the input air mass flow rate is 1.205 kg/s, thereafter it deteriorates with increasing the input air mass flow rate. The drill bit with outer diameter of 665 mm and RC-DTH air hammer with outer diameter of 400 mm were manufactured and a field test was conducted. The field test results show that the reverse circulation ability of designed large-diameter RC drill bit is well, and the maximum penetration rate in the field trial was 6.0 m/h, which could dramatically reduce the drilling operation time and cost.

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REFERENCES

1. Kahraman S, Bilgin N, Feridunoglu C. Dominant rock properties affecting the penetration rate of percussive drills. Int J Rock Mech Min. 2003;40(5):711-723.
2. Klishin VI, Kokoulin DI, Kubanychbek B, Alekseev SE, Shakhtorin IO. Substantiation of type and parameters of downhole air hammer with a view to increase small diameter hole drilling velocity. J Min Sci. 2015;51(6):1126-1131.
3. Repin A, Smolyanitsky B, Alekseev S, Popelyukh A, Timonin V, Karpov V. Downhole high-pressure air hammers for open pit mining. J Min Sci. 2014;50(5):929-937.
4. Franca LFP. A bit-rock interaction model for rotary-percussive drilling. Int J Rock Mech Min. 2011;48(5):827-835.
5. Wu D, Zhang S, He Y. A dynamic mesh-based approach to analyse hydrodynamic interactions between a fluidic hammer and drill bit. J Petrol Sci Eng. 2019;175:536-546.
6. Melamed Y, Kiselev A, Gelfgat M, Dreesen D, Blacic J. Hydraulic hammer drilling technology: developments and capabilities. J Energy Resour ASME. 2000;122(1):1-7.
7. Zhang X, Zhang S, Luo Y, Wu D. Experimental study and analysis on a fluidic hammer—an innovative rotary-percussion drilling tool. J Petrol Sci Eng. 2019;173:362-370.
8. Sun PH, Tian MJ, Cao H, Niu L, Zhang S. Study on the mechanism of ENI action on preventing drilling fluid overflowing in HDD. Tunn Undergr Sp Tech. 2018;77:94-102.
9. Xiao Y, Hurich C, Butt SD. Characterization of rotary-percussion drilling as a seismic-while-drilling source. J Appl Geophys. 2018;151:142-156.
10. Yokota T, Onishi K, Karasawa H, Ohno T, Ota A, Kaneko T. Seismic while drilling: basic experiments using a percussion drill as an energy source. Explor Geophys. 2004;35:255-259.
11. Lyons WC, Guo B, Graham RL, Hawley GD. Air and Gas Drilling Manual, 3rd edn. New York, NY: Elsevier; 2010.
12. Yin K, Wang M, Peng J, Wang R. Percussion and Rotary Drilling. Beijing: Geological Publishing House; 2010.
13. Sun B, Bònà A, Zhoub B, Werken M. A comparison of radiated energy from diamond-impregnated coring and reverse-circulation percussion drilling methods in hard-rock environments. Geophysics. 2015;80(4):K13-K23.
14. Yin Q, Peng J, Bo K, He J, Kui Y, Gan X. Study on dust control performance of a hammer drill bit. Int J Min Reclam Env. 2013;27(6):393-406.
15. Organiscak JA, Page SJ. Development of a dust collector inlet hood for enhanced surface mine drill dust capture. Int J Surf Min Reclam Env. 2005;19(1):12-28.
16. Sharma MP, Chowdhry DV. A computational model for drilled cutting transport in air (or gas) drilling operations. J Energy Resour Technol. 1986;108(1):8-14.
17. Angel RR. Volume requirements for air and gas drilling. Petrol Trans AIME. 1957;210:325-330.
18. McCray AW, Cole FW. Oil Well Drilling Technology. Tulsa, OK: University of Oklahoma Press; 1959.
19. Scott JO. How to figure how much air to put down the hole in air drilling. Oil Gas J. 1957;55:104-107.
20. Johnson PW. Design techniques in air and gas drilling: cleaning criteria and minimum flowing pressure gradients. J Can Petrol Technol. 1995;34(5):18-26.
21. Luo Y, Peng J, Li L, et al. Development of a specially designed drill bit for down-the-hole air hammer to reduce dust production in the drilling process. J Clean Prod. 2015;112:1040-1048.
22. Cao P, Chen Y, Liu M, Chen B. Optimal design of novel drill bit to control dust in down-the-hole hammer reverse circulation drilling. Arab J Sci Eng. 2017;42(2):1-12.
23. Wu D, Yin K, Yin Q, et al. Reverse circulation drilling method based on a supersonic nozzle for dust Control. Appl Sci- Basel. 2017;7(1):5.
24. Launder BE, Spalding DB. The numerical computation of turbulent flows. Comput Methods Appl Mech Eng. 1974;3(2):269-289.

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