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Experimental investigation and statistical analysis of operational parameters on temperature rise in rock drilling

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ABSTRACT

Heat generated during rock drilling, due to friction at the bit-rock interface. Due to which temperature increases, which can influence the thermal stress and subsequent rock failure. In this paper, an attempt is made to present results related to the temperature assessment during rotary drilling of rocks on medium-grained sandstone under controlled laboratory conditions. The experiments were conducted by using embedded thermocouple technique, the thermocouple was placed at a distance of 0.5mm (horizontal) from the bit-rock interface. The influence of operational parameters, i.e., the diameter of the drill bit, spindle speed and rate of penetration of rise in temperature was studied using multiple regression and data analysis was carried out using analysis of variance (ANOVA). The temperature was measured by using embedded thermocouple technique at a depth of 6mm, 14mm, 22mm and 30mm respectively. Regression models were developed for the prediction of temperature at the bit-rock interface. It was observed that the increase in temperature for medium-grained sandstone was from 49^0C to 74^0C (51.08%) with an increase in the diameter of the drill bit, spindle speed and rate of penetration.

1. INTRODUCTION

Drilling is one of the most efficient energy consuming technology processes in conducting exploration works. Nearly 80% of the energy supplied to the bit is used for heat release in terms of temperature, 1.5 to 10% for the residual changes of the bit and 3 to 5% for the destruction of rocks [1]. Temperature of the bottom hole surface increases as drilling progresses, such increase is approximately similar to the temperature variation of the flank face [2]. Heat from the rock cutting process instantly flow first to carbide insert, into the rock and the atmosphere. But the heat transfer to the atmosphere is negligible when compare to carbide bit and rock sample. Hence the conduction will take place both in rock and carbide insert assumed to be same [18]. To measure the temperature between the interface of the bit and workpiece, two type of thermocouple methods are used, i.e., welding thermocouple in bit and embedding wire in the samples, so it would form a hot junction, but the thermal inertia of welded thermocouples is high. To measure temperature with respect to better time response, a limited number of thin-wire, thermo-junction measurements to provide a transient temperature measurement data were recorded [3]. Large diameter probe, the slower was the rise in temperature this is because thicker probes had more epoxy resin filling, which delayed heat transfer from the line heat source of soil and rocks [17]. Temperature measurement with respect to time is generally a limited factor, when transient temperature changes need to be measured in solids. This technique is easy and provides an important complement to other non-contact techniques [4]. To determine the temperature at bit surface is not determined simply by a weight on bit and penetration rate, the flow resistance of grease also affects the drilling process with high temperature formation. The bearing temperature within the bit is increasing continuously during drilling [5]. To measure the pick-rock interface temperature by using copper-constantan thermocouple was introduced into the tool, the response like force, rate of penetration and depth of cut for soft and hard rock's the maximum temperature range is 2360C and 9200C [6]. Sensors are receiving heat based on the point of installation and the stabilized measurement is based on the response time [16]. Many techniques were developed to measure and observe temperature were broken in rock cutting/drilling area with small modifications but major advances of measurement techniques are still necessary to further efficiencies measure of thermal and mechanical factors [7]. A 45 MPa Indiana limestone used to perform the drilling experiment by considering the penetration to measure the temperature using RTDs to validate the accuracy of the model and the error between the predicted and the measurement values was found to 1.26^0C. [15]. A model has been developed to predict the temperature in the work piece. Out of 54 different conditions, 10 were out of the predicted range. Hence the predicted model is reasonably good for measurement of work piece temperature [8]. Laboratory scale drilling machine tests were carried out to compare the different materials such as SMART CUT (PDC) and WC as a tool to determine the temperature in quantify the frictional heat using embedded thermocouple technique [9].

As per the previous literature, resistance temperature detector was used to measure the temperature during rotary drilling [15]. In the present study, an attempt is made to implement a newly fabricated grounded thermocouple introduced in to the rock sample to measure the temperature during rock drilling. The influence of operational parameters such as drill bit diameter, penetration rate and spindle speed on temperature rise were discussed and it gives a benchmark to adopt embedded thermocouple technique and also in order to determine the effect of operational parameters on performance of the drill bit.

2. ROCK SAMPLE AND EXPERIMENTAL INVESTIGATION

2.1 Rock sample

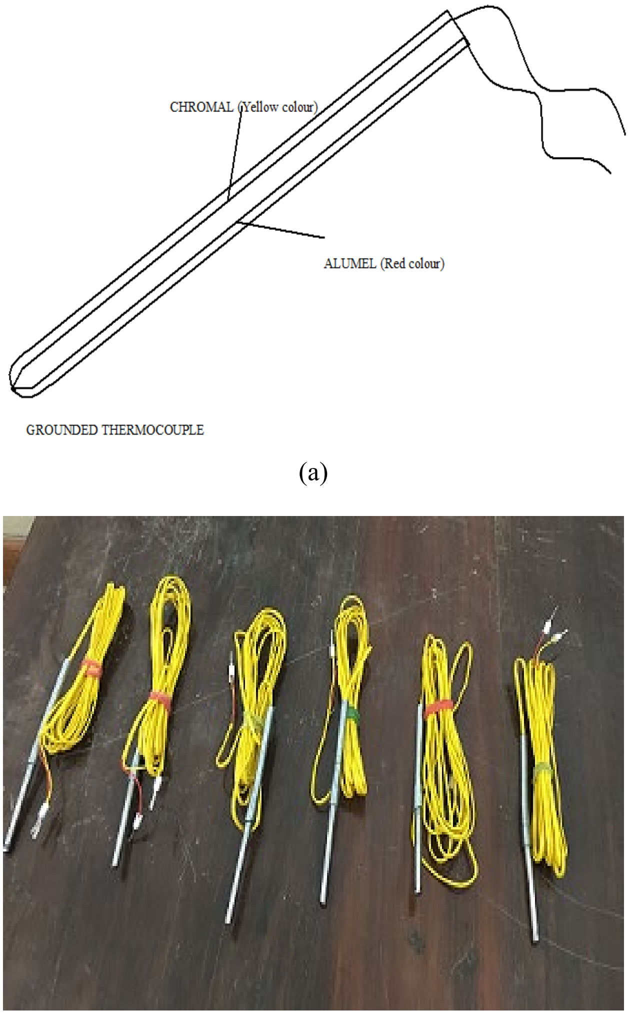
Investigations were carried out on medium-grained sandstone core samples of 54mm diameter with 135mm length as per ISRM standard and shown in Figure. 3(a). Both the ends of the samples were made parallel to each other. In the experimental procedure used by [8], the thermocouples were located at varying distances of 1.6mm, 3.2mm and 4.8mm from the bit-work piece interface, depth of 2.5mm and 5.0mm respectively in the sample. In the present study, the 3mm diameter hole was made on the surface of the rock sample called as thermocouple hole, the K- type thermocouples are inserted in to it. Several experimental difficulties were encountered, while making holes on the surface of the core samples. The main problems are location of the thermocouples in the horizontal distance and the hole diameter. With the available facilities 3mm diameter hole was selected. If the hole diameter is minimum the heat transfer can be taken place easily. It was extremely difficult to drill a hole in a rock sample with drill bit diameter smaller than 3mm.

2.2 Experimental investigation

Experiments were performed on CNC (BMV 45T20) vertical drilling machine and shown in Figure.1. The temperature at the bit rock interface was measured by a new thermocouple configuration, K-type chromel - alumel thermocouple (grounded) with an upper limit temperature of 1200^0C was designed and fabricated and shown in Figure 2(a) & (b). Based on trials, four thermocouples were used for one test condition, around 125 test conditions were conducted with different drill bit diameter, spindle speed and rate of penetration. The thermocouples (4 No's) were placed one below the other, horizontally from the top of the rock sample at a distance of 6mm, 14mm, 22mm and 30mm respectively and shown in Figure.3(a). In such a way that head of the thermocouple is 0.5mm away from the bit-rock interface and shown in Figure.3 (b). The detailed specification of the drill bit and operational parameters range is shown in Table 1. Before measuring the value of temperature all the thermocouples were checked and calibrated properly. Experiments were performed without any cooling method.

Newly fabricated grounded thermocouple (K-type). The thermocouple wire of 0.5mm diameter is inserted in to the 3mm diameter sheath material made up of stainless steel (25% chromium and 20% nickel). The wire is physically contact with the sheath material to transfer heat from the rock sample to the tip of thermocouple. As the sheath material had a high thermal conductivity in nature, heat can easily transfer from sheath material to thermocouple wire. Hence the grounded thermocouple is in physically contact with the rock sample to measure the bit-rock interface temperature. It is found that, the thermocouples are best for high temperature measurement and it is suitable for rock drilling operations.

Figure 1. CNC vertical drilling machine

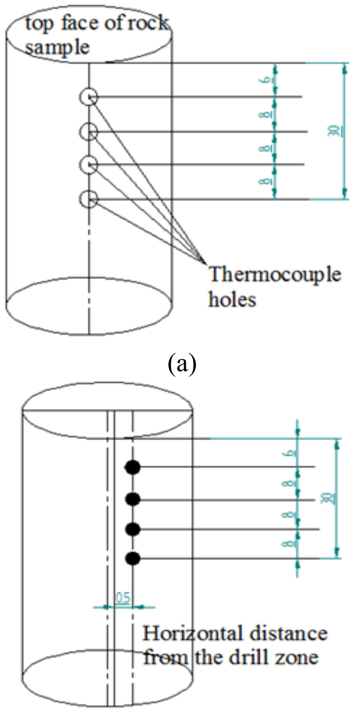


(a)

(b)

Figure 2. (a) Fabricated 2D view of thermocouple (b) Fabricated K- Type thermocouple of 3mm diameter

In general thermocouples are economical than RTD's. Installation of this type of thermocouples is very easy and replacement can be made at any stage. So, grounded thermocouple can be used for measuring bit-rock interface temperature and acquire the knowledge of thermal environment of the rock formations.



(a)

(b)

Figure 3. (a) Thermocouple holes on the surface of the rock sample (b) Two dimensional view of nominal location of thermocouple holes

Table 1. Specification of drill bit used, process parameter and their range

Masonry drill bit		
Point angle	135^0	
Bit material	Tungsten carbide	
Diameter	6,8,10,12,16mm	
Parameters	Spindle speed(rpm)	Penetration rate (mm/min)
Variable	250-450	2-10

3. RESULTS & DISCUSSION

The results obtained during rock drilling experiments are shown in Table 4-6. The influence of depth of drill, drill bit diameter, spindle speed and penetration rate of drilling temperature were investigated. After performing the experimental analysis, Analysis of variance (ANOVA) was performed to find out the significant parameters affecting an increase in temperature and shown in Table 2. Multiple regression analysis was also carried out to obtain the relationship between the operational parameters (drill bit diameter, spindle speed and penetration rate) and temperature at different depth of thermocouples and shown in Table 3.

3.1 Statistical modeling of temperature

Regression model was developed for temperature with respect to each depth of thermocouples position. In this method to observe realistic models, a backward elimination method was used as the test procedure. ANOVA was performed for bit-rock interface temperature, corresponding to thermocouple positions (6 mm, 14 mm, 22 mm, and 30 mm) with significant of 95% confidence interval. Influence of the parametric level of the temperature produced were compared using (ANOVA) with Minitab 17, where the P-values equal to or smaller than 0.05 were considered to be statistically significant and corresponding data is shown in Table 5. Multiple regression models to predict temperature for various depths of thermocouple are as follows (Eqs. (1) – (4)). The correlation coefficients (R^2) of the obtained models for the rise in temperature are 78.25%, 85.19%, 85.06% and 88.80%.

$$T_1 = 9.92 + 2.831D + 0.01544SS + 3.087PR - 0.0624D^2 - 0.1664PR^2 \tag{1}$$

$$T_2 = 11.75 + 3.960D + 0.01640SS + 2.737PR - 0.1058D^2 - 0.1257PR^2 \tag{2}$$

$$T_3 = 16.26 + 4.319D + 0.01744*SS + 3.018PR - 0.1171D^2 - 0.1271PR^2 \tag{3}$$

$$T_4 = 16.47 + 5.129D + 0.1808*SS + 3.952PR - 0.1479D^2 - 0.1721PR^2 \tag{4}$$

Table 2. Analysis of variance (ANOVA) for dependent variables (Temperatures)

Source	F-values	P-values
Temperature at 6mm depth of thermocouple	223.41	0.000
Temperature at 14mm depth of thermocouple	356.64	0.000
Temperature at 22mm depth of thermocouple	368.05	0.000
Temperature at 30mm depth of thermocouple	499.23	0.000

Table 3. Statistical analysis results of the significant parameter on regression models

Model	Variables	Coefficient	Standard error	t-value	p-value
Eq. 1	Constant	9.92	3.740	2.65	0.000
	D	2.831	0.609	4.65	0.000
	SS	0.015	0.004	3.70	0.000
	PR	3.087	0.539	5.73	0.000
	D^2	-0.062	0.027	-2.29	0.024
	PR^2	-0.166	0.044	-3.78	0.000
Eq. 2	Constant	11.75	3.300	3.56	0.001
	D	3.960	0.538	7.37	0.000
	SS	0.016	0.003	4.46	0.000
	PR	2.737	0.476	5.75	0.000
	D^2	-0.105	0.024	-4.40	0.000
	PR^2	-0.125	0.038	-3.23	0.002
Eq. 3	Constant	16.26	3.670	4.43	0.000
	D	4.319	0.598	7.22	0.000
	SS	0.017	0.004	4.26	0.000
	PR	3.018	0.529	5.70	0.000
	D^2	-0.117	0.026	-4.38	0.000
	PR^2	-0.127	0.043	-2.94	0.004
Eq. 4	Constant	16.47	3.560	4.62	0.000
	D	5.129	0.581	8.83	0.000
	SS	0.018	0.003	4.55	0.000
	PR	3.952	0.514	7.69	0.000
	D^2	-0.147	0.025	-5.70	0.000
	PR^2	-0.172	0.042	-4.10	0.000

3.2 Influence of depth of drill on temperature

Influence of depth of drill on bit-rock interface temperature was studied and a range was selected from 6mm to 30mm. Generally, as the depth of drill increases, it causes an increase in drilling temperature. This is because of the energy required to drill the rock is proportional to the amount of new surface area produced [9]. It is also noted that the average maximum drilling temperature increased is about 18.75% from 48^{0}C to 57^{0}C when the depth of the drill increased from 6mm to 14mm. However when the depth of drill increased from 22mm to 30mm, the drilling temperature rise only about 12.12% from 66^{0}C to 74^{0}C and shown in Figure 4. This may partly because of specific energy was reaching a saturated value with the increasing depth [10].

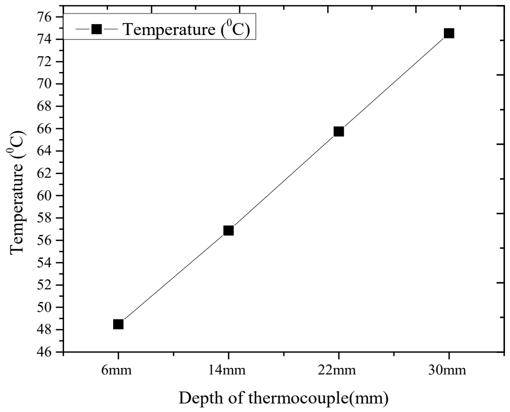


Figure 4. Effect of depth of thermocouples on rise in temperature

3.3 Influence of drill bit diameter on temperature

Influence of drill bit diameters on temperature rise was studied and shown in Figure.5 It has been found that the temperature increased with increase in drill bit diameter from 6mm to 16mm. It may be due to the contact surface between the bit-rock interface increases as the bit diameter increases, which leads to increase in volume removal rate and thermal resistance [14].

Table 4. Average temperatures of medium grained sandstone for different drill bit diameters

Drill bit diameter (mm)	Temp. at 6mm depth(^{0}C)	Temp. at 14mm depth(^{0}C)	Temp. at 22mm depth (^{0}C)	Temp. at 30mm depth (^{0}C)
6	42.40	49.36	58.20	66.12
8	42.52	51.12	59.64	69.08
10	50.00	58.04	66.52	75.88
12	51.88	61.48	71.48	80.32
16	55.60	64.36	74.00	84.72

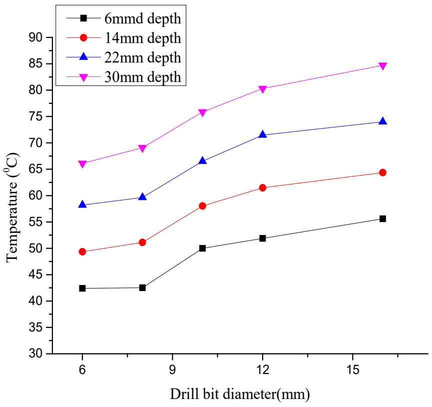


Figure 5. Effect of drill bit diameter on rise in temperature for different depth of thermocouples

3.4 Influence of penetration rate on temperature

The effect of penetration rate on temperature and shown in Figure. 6. Drill bit diameter and spindle speed was kept constant to analyze the effect of penetration rate. The temperature increases significantly with increasing rate of penetration from 2mm/min to 10mm/min. It may be due to increase in the penetration rate, causing increases in volume removal rate, thermal stress and heat generation [11].

Table 5. Average temperatures of medium grained sandstone for different penetration rate

Penetration rate (mm/min)	Temp. at 6mm depth (^{0}C)	Temp. at 14mm depth (^{0}C)	Temp. at 22mm depth (^{0}C)	Temp. at 30mm depth (^{0}C)
2	42.52	50.80	58.6	65.12
4	47.48	55.24	63.68	72.68
6	49.88	57.84	66.48	75.20
8	50.72	59.56	69.20	78.72
10	51.80	60.92	70.76	80.96

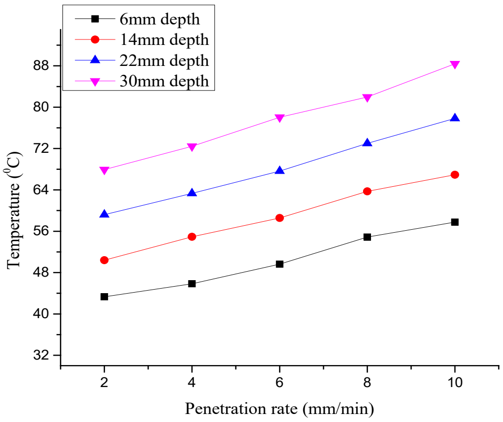


Figure 6. Effect of penetration rate on temperature for different depth of thermocouple

3.5 Effect of spindle speed on temperature

Influence of spindle speed on temperature and shown in Figure.7. The temperature increases with increase in spindle speed from 250 rpm to 450 rpm. It is due to the high contact area [12]. It is evident that heat flow in the bit and rock are increased due to clogging of dust and chips in between the interface, also more frictional force and shearing energy between the bit-rock interfaces, hence the drilling temperature increases.

Table 6. Average temperatures of medium grained sandstone for different spindle speeds

Spindle Speed (rpm)	Temp. at 6mm depth (^{0}C)	Temp. at 14mm depth (^{0}C)	Temp. at 22mm depth (^{0}C)	Temp. at 30mm depth (^{0}C)
250	46.96	54.96	63.92	72.4
300	47.24	55.92	64.68	73.76
350	49.08	57.92	66.32	75.00
400	49.36	57.08	66.36	75.44
450	49.76	58.48	67.44	76.08

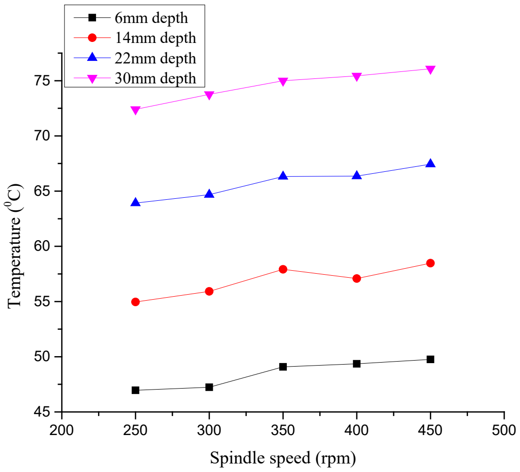
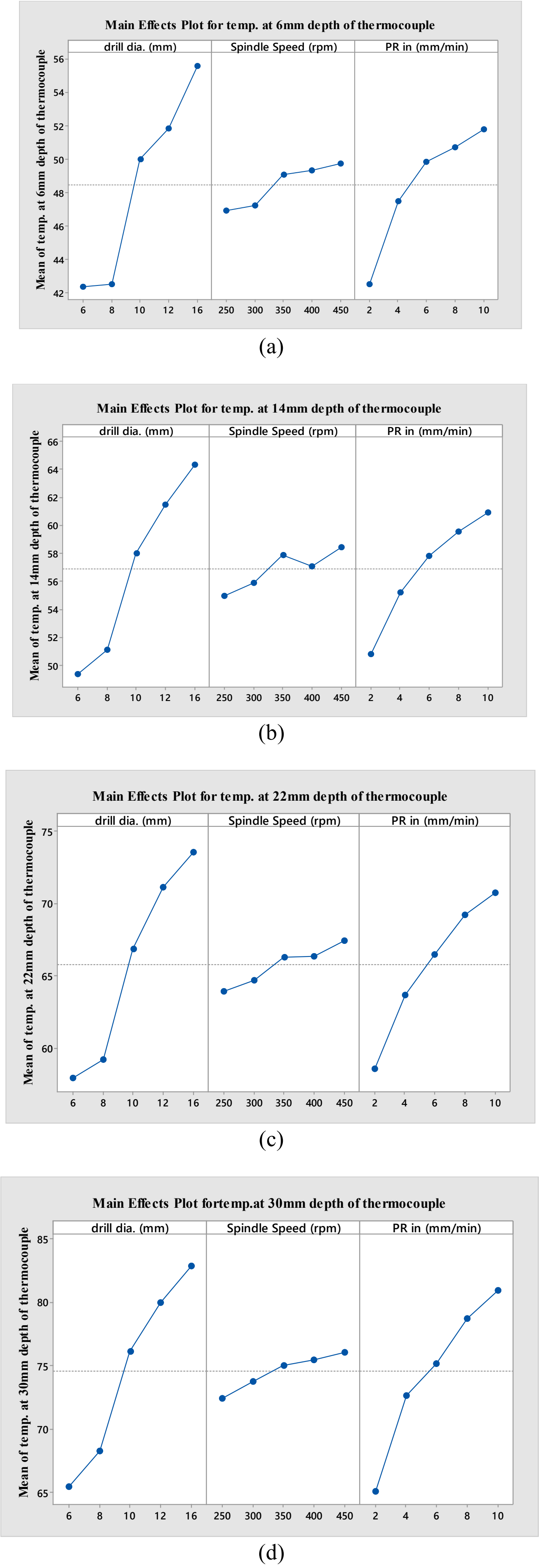


Figure 7. Effect of spindle speed on rise in temperature for different depth of thermocouple

3.6 Main effect plots

Figure.8 (a)-(d) shows that main effect plots of the operating parameters. The highest slope tends more significant in the model. The steeper the slope of the line in this investigation is penetration rate followed by drill bit diameter. The results of the statistical analysis showed that the drill bit diameter and penetration rate have the more influencing parameter on temperature rise, followed by the spindle speed, because the area of the rock contact with bit surface is more from smaller drill-bit to larger drill-bit. The thermal energy required is also more. The results show that the effect of penetration rate followed by the bit diameter and spindle speed has a similar effect, where the temperature increases exponentially with an increase in all three parameters.



(a)

(b)

(c)

(d)

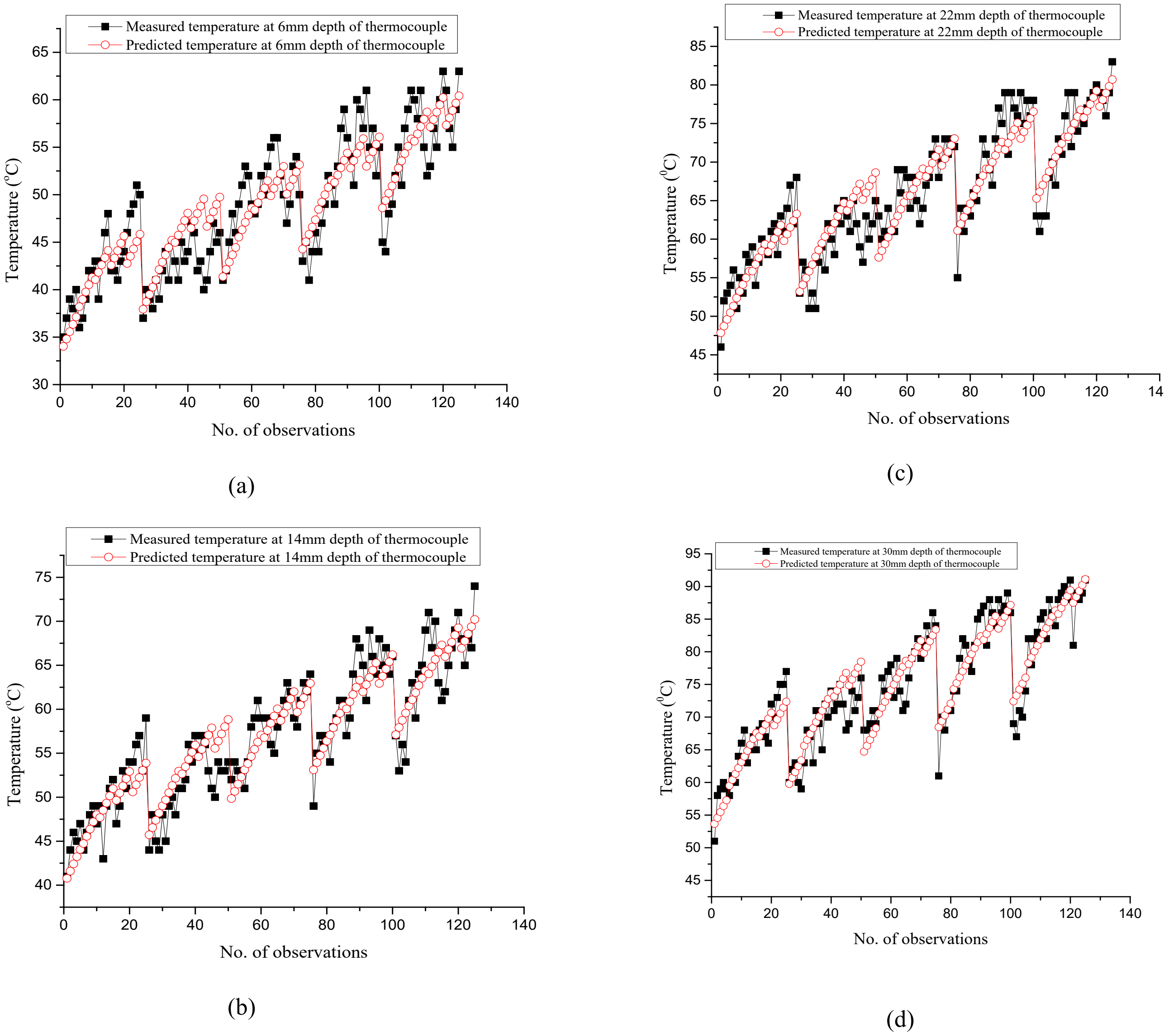
Figure 8. Main effect plots of operation parameter on temperature (a-d)

3.7 Validation of predicted models

The statistical results of the medium-grained sandstone models are given in Eqs. (1-4). To realize the predicted ability of the derived models, the scatter diagrams of the predicted and measured data were plotted and shown in Figure. 9 (a-d). Plots show that, the predicted value using regression models are very close to the of measured temperature data. When this happens most of the point lying on the line indicates an exact prediction. These results indicate that multiple regression models suggesting that the models are reasonably good [13]. And also in the confirmation of experiments, different operational parameters for drill bit diameter (4mm, 18mm), spindle speed (200rpm, 500rpm), penetration rate (2mm/min, 10mm/min) were considered with a selected range and shown in Table 7.

Table 7. Validation of models for Medium-grained sandstone

Drill bit diameter (mm)	Spindle speed (rpm)	Penetration rate (mm/min)	Medium-grained sandstone (Temperature in ^{0}C)							
			From Model	From exp.	From Model	From exp.	From Model	From exp.	From Model	From exp.
			T_1	T_1	T_2	T_2	T_3	T_3	T_4	T_4
4	200	2	28.84	35	34.15	35	40.67	43	45.45	48
18	500	10	62.61	66	71.85	74	82.25	88	92.22	96



(a)

(c)

(b)

(d)

Figure 9. Predicted and measured temperatures of medium-grained sandstone for all depths of thermocouple (a-d)

4. SUMMARY AND CONCLUSIONS

In this paper, a new experimental technique has been introduced for the measurement of temperature during rock drilling operation and equivalent statistical models have also been developed for measuring temperature. Effects of operational parameters on the rise in temperature at different depth of thermocouples between the bit-rock interfaces were investigated. From the present study it was concluded that the temperature increased by 51.08% from 49^0C to 74^0C, with an increase in rate of penetration, spindle speed and diameter of the drill bit. Regression models for prediction of bit-rock interface temperatures were developed. Predicting performance of the given model is good and a confidence interval of 95%, predictive interval was statistically significant within the expected range.

Temperature rise during continuous drilling of medium-grained sandstone. It was concluded that the bit-rock interface temperature concerning drill bit diameter (6mm to 16mm) temperature increased around 27.30%. The bit-rock interface temperature concerning penetration rate (2mm/min to 10mm/min) temperature increased around 54.72%. The effect of bit-rock interface temperature concerning spindle speed (250rpm to 450rpm) temperature increased is around 2.3% was smaller than that of the drill bit diameter and penetrationrate. Hence penetration rate is the most infuencing parameter followed by the drill bit diameter and spindle speed.

REFERENCES

[1] Dreus A, Kozhevnikov A, Lysenko K, Sudakov A. (2016). Investigation of heating of the drilling bits anddefinition of the energy efficient drilling modes. Eastern European Journal of Enterprise Technologies 3: 41-46. https://doi.org/10.15587/1729-4061.2016.71995

[2] Sato M, Aoki T, Tanaka H, Takeda S. (2013). Variation of temperature at the bottom surface of a hole during drilling and its effect on tool wear. International Journal of Machine Tools & Manufacture 68: 40-47. https://doi.org/10.1016/j.ijmachtools.2013.01.007

[3] Agapiou JS, Stephenson DA. (1994). Analytical and experimental studies of drill temperatures. Transaction of American Society of Mechanical Engineering Journal of Engineering for Industry 116: 54-54. https://doi.org/10.1115/1.2901809

[4] Rittel D. (1998). Transient temperature measurement using embedded thermocouples. Experimental Mechanics 38: 73-78. https://doi.org/10.1007/bf02321647

[5] Suto Y, Takahashi H. (2011). Effect of the load condition on frictional heat generation and temperature increase within a tri-cone bit during high-temperature formation drilling. Geothermics 40: 267-274. https://doi.org/10.1016/j.geothermics.2011.08.004

[6] Louie PJ, Rao KUM. (1997). Experimental Investigations of pick-rock interface temperature in drag-pick cutting. International Journal of Engineering and Material Sciences 4: 63-66.

[7] Che D, Han P, Guo P, Ehmann K. (2012). Issues in polycrystalline diamond compact cutter–rock interaction from a metal machining point of view—par i: Temperature, stresses, and forces. Journal of Manufacturing Science & Engineering 134: 64001. https://doi.org/10.1115/1.4007468

[8] Bono M, Ni J. (2002). A model for predicting the heat flow into the workpiece in dry drilling. Journal of Manufacturing Science & Engineering 124: 773-777. https://doi.org/10.1115/1.1511176

[9] ShaoW, Li XS, Sun Y, Huang H. (2014). Laboratory comparison of SMART* CUT picks with WC picks. Advanced Materials Research, Trans Tech Publication 1017: 323-328. https://doi.org/10.4028/www.scientific.net/amr.1017.323

[10] Roxborough FF. (1985). Research in mechanical rock excavation: Progress and prospects. In Proceedings of the Rapid Excavation Tunnel Congress, Las Vegas, pp. 225-244

[11] Zhang H, Boyun G, Deli G, Huang H. (2016). Effect of rock properties and temperature differential in laboratory experiments on underbalanced drilling. International Journal of Rock Mechanics and Mining Sciences 83: 248-251. https://doi.org/10.1016/j.ijrmms.2014.08.004

[12] Samy GS, Kumaran T. (2017). Measurment and analysis of temperature, thrust force and surface roughness in drilling of AA (6351)-B4C composite. Measurement 103: 1-9. https://doi.org/10.1016/j.measurement.2017.02.016

[13] Kumar BR, Vardhan H, Govindaraj M, Vijay GS. (2013). Regression analysis and ANN models to predict rock properties from sound levels produced during drilling. International Journal of Rock Mechanics and Mining Sciences 58: 1-72. https://doi.org/10.1016/j.ijrmms.2012.10.002

[14] Gupta V, Pandey PM. (2016). Experimental investigation and statistical modeling of temperature rise in rotary ultrasonic bone drilling. Medical Engineering Physics 38: 1330-1338. https://doi.org/10.1016/j.medengphy.2016.08.012

[15] Szwarc T, Akul A, Hubbard S, Cantwell B, Zacny K. (2012). A thermal model for analysis and control of drilling in icy formations on mars. Planetary and Space Science 73: 214-220. http://dx.doi.org/10.1016/j.pss.2012.09.003

[16] Chmura K, Suschka M, Twardoch S. (1996). Automatic and continuous measurements of temperature in mining headings. Journal of Thermal Analysis 38: 2189-2194. https://doi:10.1007/BF01979633

[17] Lee JS, Chan CJ, Baek S, Hyuk KT, Hwan RH, SongK. (2016). Use of a pre-drilled hole for implementing thermal needle probe method for soils and rocks. Energies 846: 1-10. https://doi.org/10.3390/en9100846

[18] Matin JA, FowellJR. (1997). Factors governing the onset of severe drag tool wear in rock cutting. International Journal of Rock Mechanics and Mining Sciences 34: 59-69. https://doi.org/10.1016/S1365-1609(97)80033-0

NOMENCLATURE

D = Drill bit diameter (mm)
SS= Spindle speed (rpm)
PR= Penetration rate (mm/min)
T_1=Temperature at 6mm depth of thermocouple (^{0}C)
T_2= Temperatureat 14mm depth of thermocouple (^{0}C)
T_3= Temperature at 22mm depth of thermocouple (^{0}C)
T_4 = Temperature at 30mm depth of thermocouple (^{0}C)