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Thermodynamically Predicting the Impact of Temperature on the Performance of Drilling Bits as a Function of Time

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ABSTRACT

Air drilling has recently received increasing acceptance by the oil and gas industry due to its unique advantages. The main advantages of air drilling include higher rate of penetration, less formation damage, lower risk of loss of circulation. However, these advantages cannot be fully realized if thermal effects in air drilling are not well understood and minimized. Due to its high frictional coefficient, low heat conductivity, and high compressibility, air can impact the temperature distribution of bit and thus affect its bit performances. Based on energy and mass balances, a transient thermal model that predicts bit temperature is presented along with numerical solutions in this paper. In addition, several important parameters that influence bit temperature distribution are analyzed. Simulation results show that the bit temperature increases with increasing weight on bit and rotary speed but decreases as the standpipe pressure and flow rate increase. These results can be used to optimize drilling operations and flow parameters for an improved bit performance as shown in this paper.

Keywords: air drilling, bit temperature, rate of penetration, frictional coefficient, weight on bit, rotary speed, thermal conductivity of air.

1. INTRODUCTION

Since its introduction in the early 1950’s, air or gas drilling has been widely used due to its advantages, such as higher rate of penetration (ROP), minimum formation damage, lower risk of loss of circulation and early detection of hydrocarbons (Cooper, *et al*. 1977; Wilson, 1981). Among these advantages, higher ROP is the most attractive one. Wilson (1981) pointed out that air drilling can increase rate of penetration by a factor of four when compared with mud drilling.

Rock penetration is achieved by the action of the bit. It is agreed upon that he bit performance is greatly influenced by its temperature. Glowka *et al*. (1986) found that bit performance deteriorated under high temperature condition. This problem becomes serious in air drilling because of the unique properties of air.

Compared with normal mud drilling, more heat is generated, during air drilling, due to the high friction coefficient. In addition, due to its low conductivity, heat dissipation during air drilling is much less than that of normal mud drilling. Therefore, the bit temperature increases quickly if improper drilling operation and flow parameters are applied.

Weight on bit (WOB) and rotary speed, affect the bit temperature during drilling. It is well accepted that increasing the weight on bit and rotary speed can increase the rate of penetration during drilling (Bourgoyne *et al.* 1991). However, more frictional energy is generated as the weight on bit and rotary speed increase, especially in air drilling, because the frictional coefficient between bit and formation surfaces is much higher for air than mud. Moreover, the heat conductivity of air is much lower than that for water and therefore the thermal energy cannot dissipate easily, which causes the bit temperature to increase significantly if improper flow and drilling operation parameters are employed. The increase in bit temperature can lead to premature bit deterioration which could ultimately lead to its failure. Glowka, *et al*. (1986) found that PDC (polycrystalline Diamond Compact) cutter wear rates increase one to two orders of magnitude when cutter wear flat temperatures exceed a critical value of about 350^{o}C (662^{o}F). Ortega, *et al*. (1984) set 750^{o}C (1382^{o}F) as the maximum safe operating temperature for PDC/WC cutters.

In addition to weight on bit and rotary speed, flow rate and standpipe pressure affect the bit temperature. Many researchers put their focus on studying the hydraulic effects in air drilling (Mitchel, 1983; Cummings, 1987; and Adewumi, *et al.*, 1990). However, the consideration in determining the flow rate is only based on hole cleaning (Cooper, 1977). Cummings, (1987) pointed out that gas volume requirements are determined for adequate hole cleaning, carry capacity to surface, and drill string cooling as functions of drilling depth, annular cross sectional area, penetration rate, and gas gravity. Relatively speaking little is known about thermal effects of flow rate and standpipe pressure in air drilling even though it significantly influences the bit performance.

2. TRANSIENT BIT TEMPERATURE MODEL

2.1 Assumptions

As indicated in Figure 1, the bit, as well as the air within it, is taken as the control volume (CV). Before developing the bit thermodynamics model, we shall make the following assumptions:

a. The temperature is uniform across the bit.
b. The air temperature is the same as the bit.
c. The heat capacity of the bit is constant.
d. Air between bit and wellbore surfaces is adiabatic.
e. The change in pressure due to change in elevation is negligible.
f. The frictional loss across the bit is ignored.

2.2 Thermodynamic Model

As shown in Figure 1, the air enters the control volume at plane 1 with cross section A_1 and leaves at plane 2 with cross section A_2. The pressure and average velocity are P_1 and $\overline{V}_1$ at the entry plane, P_2 and $\overline{V}_2$ at the exit plane respectively.

The energy balance can be expressed in words as

(Energy into CV) - (Energy from CV) = (Accumulation of energy in CV)

After considering kinetic energy, works, potential energy, heat, and internal energy, we obtained the thermodynamic model to predict the bit temperature as a function of time.

The energy terms including kinetic energy, works, potential energy, heat, and internal energy should be included in energy balance equation, which will be discussed term by term as follows.

Kinetic energy. Kinetic energy into the CV at Plane 1(see Figure 1) can be calculated as

$$\frac{1}{2}\rho_{a1}A_1\overline{V}_1^{\,3}dt \tag{1}$$

, and kinetic energy out

$$\frac{1}{2}\rho_{a2}A_2\overline{V}_2^{\,3}dt \tag{2}$$

Works. Works done to the CV by the surroundings at Plane 1 is given by

$$P_1\overline{V}_1A_1dt \tag{3}$$

, and works done to the surroundings at Plane 2

$$P_2\overline{V}_2A_2dt \tag{4}$$

Based on assumption, air flows from Plane 1 to 2 is an isothermal process, so we have

$$P_1\overline{V}_1A_1dt = P_2\overline{V}_2A_2dt \tag{5}$$

Therefore the works term in energy balance equation can be ignored.

Thermal energy. Thermal energy into the bit is given by

$$E_{bh}dt \tag{6}$$

Internal energy. Internal energy generation by conduction can be calculated as

$$\left(m_b\hat{C}_{pb} + \overline{\rho}_{ab}\hat{C}_{Pa}V_{ab}\right)\cdot dT \tag{7}$$

According to the assumption, the potential energy along the bit is ignored. So the energy balance equation can be expressed as

$$\left[\frac{1}{2}\left(\rho_{a1}A_1\overline{V}_1^{\,3}-\frac{1}{2}\rho_{a2}A_2\overline{V}_2^{\,3}\right)+E_{bh}\right]dt=\left(m_b\hat{C}_{ps}+\rho_a V_{ab}\hat{C}_{Pa}\right)\cdot dT \tag{8}$$

Based on mass balance,

$$\rho_{a1}A_1\overline{V}_1=\rho_{a2}A_2\overline{V}_2=w=cons\tan t \tag{9}$$

The Equation (A-8) can be modified as

$$\left[w\left(\overline{V}_1^{\,2}-\overline{V}_2^{\,2}\right)+2E_{bh}\right]dt=2\left(m_b\hat{C}_{ps}+\rho_{ab}\hat{C}_{Pa}V_{ab}\right)dT \tag{10}$$

The determination of the parameters appeared in the above equation is discussed as follows.

Mass flow rate. If the volume flow rate is expressed as standard cubic feet per minute (SCFM), the mass flow rate can be calculated as

$$w=0.1729\frac{MQ_s}{zR} \tag{11}$$

Gas density. The gas behavior can be described using the real gas equation defined as

$$PV=z\frac{m}{M}RT \tag{12}$$

Therefore the gas density can be expressed as a function of pressure and temperature

$$\rho_a=\frac{PM}{zRT} \tag{13}$$

Hydrostatic pressure in gas columns. The pressure change in a micro-element of a gas section can be expressed as

$$dP=\rho_a gdD \tag{14}$$

Substituting Equation (A-13) into (A-14) and integrating produce an equation for calculating hydrostatic pressure in air volumes given by

$$P=P_s e^{\frac{MDg}{zRT}} \tag{15}$$

Average velocities at the inlet and outlet of the bit. Substituting Equations (A-13) and (A-15) into (A-9) yields

$$\overline{V}_1=\frac{wzRT_b}{MP_s e^{\frac{MDg}{zRT_b}}A_1} \tag{16}$$

$$\overline{V}_2 = \frac{wzRT_b}{MP_s e^{\frac{MDg}{zRT_b}} A_2} \quad (17)$$

Here the length of the bit is ignored because it is small compared with the length of the drill string.

Heat capacity of air. Assume turbulent flow and ideal gas behavior, and use the following expression for the heat capacity of air (Bird, *et al*. 2002)

$$\hat{C}_{Pa} = 512.11 + 0.14T - \left(2 \times 10^{-5}\right)T^2 \quad (18)$$

Thermal energy absorbed by the bit. During drilling operation, frictional energy is generated by the bit when it rotates with speed n under certain value of weigh on bit (WOB), as indicated in Figure A-1. In order to determine the frictional energy generated by the bit, we assumed that the bit surface is flat.

The rate of frictional energy generated by the bit can be derived as

$$E_b = \int_0^{r_b} 2\pi rn \cdot f \cdot \frac{W_b}{\pi r_b^2} \cdot 2\pi r \cdot dr = \frac{4\pi \cdot r_b W_b \cdot n \cdot f}{3} \quad (19)$$

Note that f in Equation (A-19) is the coefficient of friction between bit and formation surfaces. It was pointed by Ortega, *et al.* (1984) and Glowka, *et al*. (1986) that there is big difference of frictional coefficients between air and mud drilling. It is much higher for air drilling than that for water drilling, which is assumed to be 0.3 for air and 0.1 for water drilling respectively in our discussion.

Much of the above frictional energy is consumed in breaking formation and some of it is converted into heat (thermal energy) absorbed by the bit. An equation to calculate the rate of thermal energy absorbed by the bit can be expressed as

$$E_{bh} = \alpha \cdot E_b = \frac{4\pi \cdot r_b W_b \cdot n \cdot f \cdot \alpha}{3} \quad (20)$$

Note that in Equation (A-20) α is the fraction of frictional energy conducted into the bit. It is influenced by the thermal properties of the bit and formation (Glowka, *et al*. 1985). Ortega, *et al*. (1984) introduced a method to determine this parameter. It lies in the range of 0.1 to 0.8, which is assumed to be 0.2 in our discussion.

Substituting all the above relationships into Equation (A-10) and doing some arrangements, we have

$$\frac{dT}{dt} = \frac{\left\lfloor wT^2 c_1^{\,2} \cdot e^{-2c_2/T} + 2E_{bh} \right\rfloor}{2\left(m_b \hat{C}_{pb} + \dfrac{e^{c_2/T} \hat{C}_{Pa}}{c_1 T} \right)} \tag{21}$$

where,

$$c_1 = \frac{wzR}{MP_s} \tag{22}$$

$$c_2 = \frac{MDg}{zR} \tag{23}$$

In the above equation, w is mass flow rate, T bit temperature, z gas deviation factor, R gas law constant, M air molecular weight, Ps standpipe pressure, D true vertical depth, g standard acceleration of gravity, E_{bh} thermal energy absorbed by the bit, mb mass of the bit, $\hat{C}_{Pb}$ heat capacity of the bit, and $\hat{C}_{Pa}$ the heat capacity of air.

3. RESULTS AND APPLICATIONS

After the transient thermal model to predict bit temperature has been developed, it can be used to analyze the effects of drilling operation and flow parameters on bit temperature. The data used in the analysis are shown in Table 1.

3.1 Effects of Flow Parameters

3.1.1 Air flow rate

Generally the flow rate is determined according to adequate hole cleaning in air drilling (Cooper *et al*., 1977; Cummings 1987; Adewumi 1989 and 1990; Allan 1994). In fact, in addition to hole cleaning, the flow rate also affects the bit thermal response. Convective cooling plays a key role in defining bit thermal response and, hence bit temperature. By assuming weight on bit and rotary speed to be 30,000 lb_f and 50 rpm respectively, the effects of flow rate on bit temperature are illustrated in Figure 2. Three aspects can be observed from this figure. Firstly, the bit temperature increases with time and levels off after certain period of time for each flow rate. This is because the thermal energy absorbed by the bit is larger than that carried away by the air. So the bit temperature increases at the beginning. This increase in bit temperature causes the flow velocity to increase at the outlet of the bit, as indicated in Equations (A-17), so more energy is taken away from the bit by forced convection. When the rate of thermal energy absorbed by the bit is equal to that carried away from the bit by air flow, the bit temperature levels off. Secondly, it can be seen that the lower the flow rate, the longer it takes to reach equilibrium. And finally, the higher the flow rate, the lower the equilibrium temperature. Therefore, increasing the air flow rate is also beneficial to bit cooling as well as hole cleaning, Ortega *et al.* (1984) stated that it is possible to increase the convection cooling by increase the local velocity at bit nozzles through modifications of the hydraulic design.

3.1.2 Standpipe pressure

In air drilling, high bottom hole velocity is necessary for hole cleaning which causes high frictional pressure loss in drill pipe and annulus. So high standpipe pressure is required for air drilling (Mitchell 1993). For example, in drilling three nitrogen horizontal wells in the San Juan Basin of New Mexico, the required standpipe pressure is in the range of 500-1500 psi (Allan 1994). The effects of standpipe pressure on bit temperature are shown in Figure 3. It is seen that the bit temperature increases with increasing the standpipe pressure. This result is counter intuitive considering the unique property of the compressible flow. It can be explained by using Equations (A-16) and (A-17) that the average velocity is inversely proportional to standpipe pressure. So the higher the standpipe pressure, the lower the average air velocity and lower that amount of heat that is carried away by forced convection. This is the reason why the bit temperature increases with the increasing the standpipe pressure. From the above analysis, we see that both the flow rate and the standpipe pressure affect the bit temperature. Therefore, it is necessary to consider the combined effects of flow rate and standpipe pressure on the bit temperature and performance when drilling operation parameters are determined.

3.1.3 Determination of flow rate and standpipe pressure

Assuming that the weight on bit and rotary speed are 30,000lb_f and 50 rpm respectively, the combined effect of flow rate and standpipe pressure is shown in Figure 4. This figure can be used to determine the proper flow parameters. For example, if the bit works at temperature below 1000^oF, flow rate should be higher than 1400SCFM when the standpipe pressure equals 1000 psi.

3.2 Drilling Media

As mentioned previously, the differences between water and air drilling are frictional coefficient, compressibility, and heat capacity. The changes of temperature with time for air and water drilling are compared in Figure 5. It is seen that the temperature increases much faster for air than that for water drilling, so thermal effects should be stressed in air drilling to avoid bit failure. In addition, bit temperature nearly keeps constant in water drilling due to its incompressible property. There is no change for the velocities at the inlet and outlet of the bit. The rate of thermal energy absorbed by the bit nearly equals that taken away from the bit under the simulation condition, so the bit temperature keeps unchanged. Finally it is important to see, in this figure, that the bit temperature increases significantly in drilling without circulation. This is because the bit cannot be cooled by forced convection. Therefore, it is important to start drilling after air has reached to the bit. Cooper (1977) stated that “It is absolutely necessary to have air circulating around the bit before drilling is started. This prevents dry drilling and prolongs bit life”

3.3 Effects of Drilling Operation Parameters

3.3.1 Weight on bit

The effect of weight on bit on bit temperature is shown in Figure 6. It is seen that bit temperature increases with time at the beginning, and sometime later equilibrium is reached. The equilibrium temperature increases as the weight on bit increases.

3.3.2 Rotary speed

Figure 7 shows the effects of rotary speed on bit temperature. Similar to the effects of weight on bit, the equilibrium temperature increases as the rotary speed increases. Based on the results from the above analysis, the optimal combination of weight on bit and rotary speed can be determined.

3.3.3 Determination of weight on bit and rotary speed

Weight on bit and rotary speed are two key parameters that should be determined during drilling operation. Normally they are designed based on the types of the bit used and the formation drilled. The combined effects of weight on bit and rotary speed are illustrated in Figure 8. This figure can be used to determine the drilling operation parameters under certain flow conditions. For example, if we assume that a bit working temperature of 600 ^{0}F, the weight on bit cannot exceed 54,000 lb_f when the rotary speed is equal to 50 rpm.

4. CONCLUSIONS

1) Based on mass and energy balances, a transient thermal model to predict bit temperature is developed.
2) Bit temperature increases with increasing weight on bit and rotary speed. And it decreases as standpipe pressure and flow rate increase.
3) The results can aid in drilling operation and flow parameters optimization.
4) Bit temperature increases much faster in air drilling than that in water drilling.
5) Dry drilling must be avoided in air drilling.

Nomenclatures*

A_1	Inlet area of the bit [=] L^2
A_2	Nozzles area of the bit [=] L^2
$\hat{C}_{pa}$	Heat capacity of the air within the bit [=] L^2/t^2-K
$\hat{C}_{pb}$	Heat capacity of the bit [=] L^2/t^2-K
D	True vertical depth of well [=] L
E_b	Frictional energy generated by the bit [=] mL^2/t^2
E_{bh}	Rate of frictional heat energy generated by bit [=] mL^2/t^3

f	Frictional coefficient between bit and rock, dimensionless
g	Standard acceleration of gravity, 9.8065 m/s^2
K_f	Formation thermal conductivity [=] $W/cm\cdot^{\circ}C$
m	Mass of air [=] m
m_b	Mass of the bit [=] m
M	Air molecular weight, g/mol
n	Rotary speed, rpm
P_1	Absolute pressure at the inlet of the bit [=] $m/L\text{-}t^2$
P_2	Absolute pressure at the outlet of the bit [=] $m/L\text{-}t^2$
P_s	Standpipe pressure [=] $m/L\text{-}t^2$
Q_s	Air volume flow rate at surface, SCFM;
r_b	Bit radius [=] L
R	Gas law constant, $8.31451\times10^3 kg\cdot m^2/S^2\cdot Kg-mole\cdot K$;
t	Time [=] t
T_b	Bit temperature [=] T
V	Air volume [=] L^3
$\overline{V}_1$	Average velocity at the inlet of the bit [=] L/t
$\overline{V}_2$	Average velocity at the outlet of the bit [=] L/t
V_{ab}	Volume of air within the bit [=] L^3
w	Mass flow rate [=] m/t
W_b	Weight on bit [=] mL/t^2
z	Gas deviation factor, dimensionless
α	Fraction of frictional energy transferred to heat.
ρ_a	Air density [=] m/L^3
ρ_{a1}	Air density at the inlet of the bit [=] m/L^3
ρ_{a2}	Air density at the outlet of the bit [=] m/L^3
$\overline{\rho}_{ab}$	Average density of air within the bit, [=] m/L^3

* [=] means has units of, L is a length unit, m mass, t time, and T temperature

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Table 1 – Data used in analysis.

Bit radius (in)	4.25
Weight on bit (lbf)	30000
Rotary speed (rpm)	50
Coefficient of friction for air	0.3
Coefficient of friction for water	0.1
Heat transfer factor	0.2
Inlet area, A_1 (in^2)	62
Nozzle area, A_2 (in^2)	0.38
Heat capacity of bit(J/kg.K)	230
Bit weight(Kg)	30
Standpipe pressure (psi)	1000
Surface temperature (^oF)	80
Surface flow rate (ft^3/m)	2000
Well Depth (ft)	10000
Molecular weight of Air	29
Gas deviation factor	1
Formation Temperature, T_f(^OF)	140
Initial Temperature (^OF)	100
Air Volume inside the Bit (cm^3)	4000
Gas Constant (J/Kg-mol·k)	8314.51
Standard acceleration of gravity	9.8065

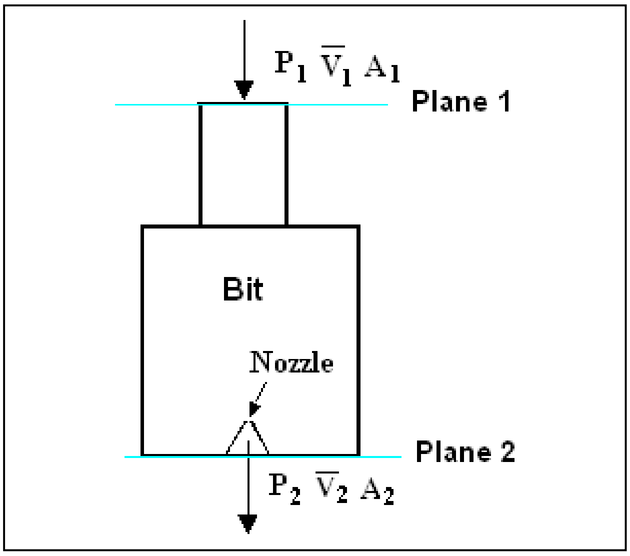

Figure 1 - Drilling bit system.

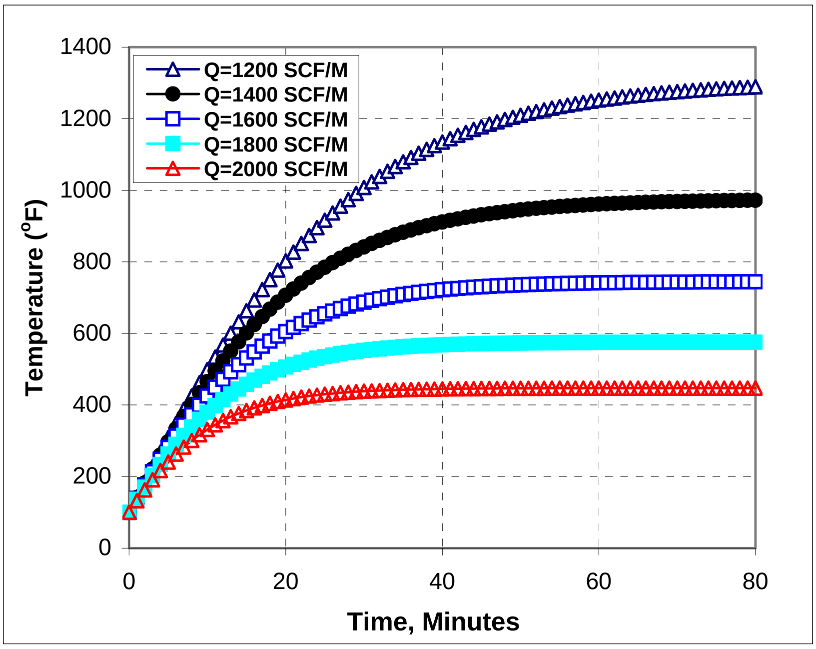

Figure 2 - Influence of flow rate on bottom hole bit temperature.

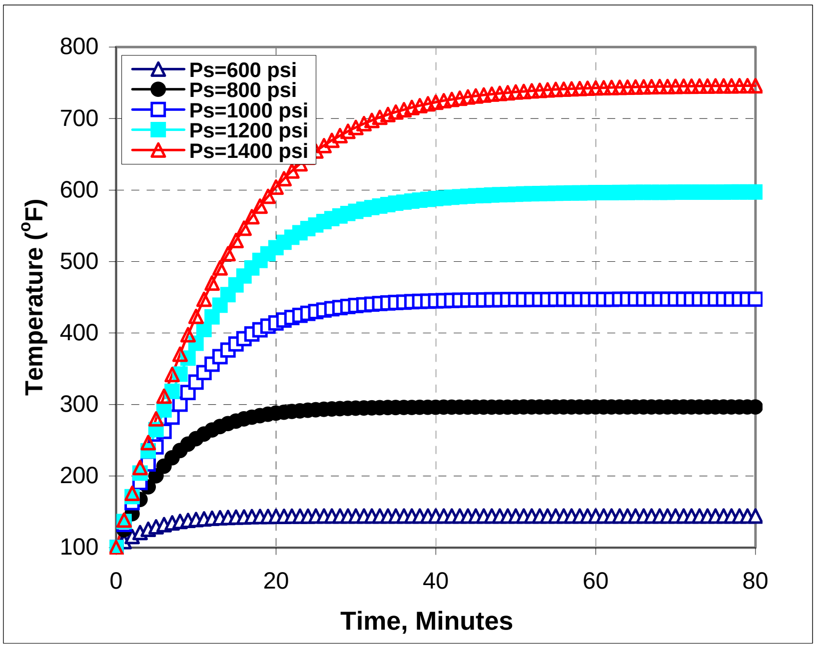

Figure 3 - Influence of surface pressure on bit temperature.

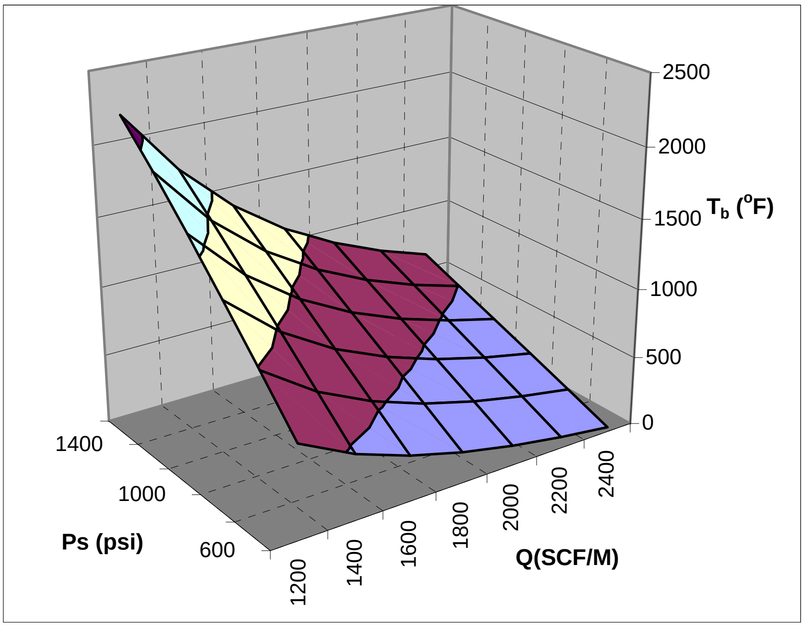

Figure 4 - Determination of flow rate and surface pressure.

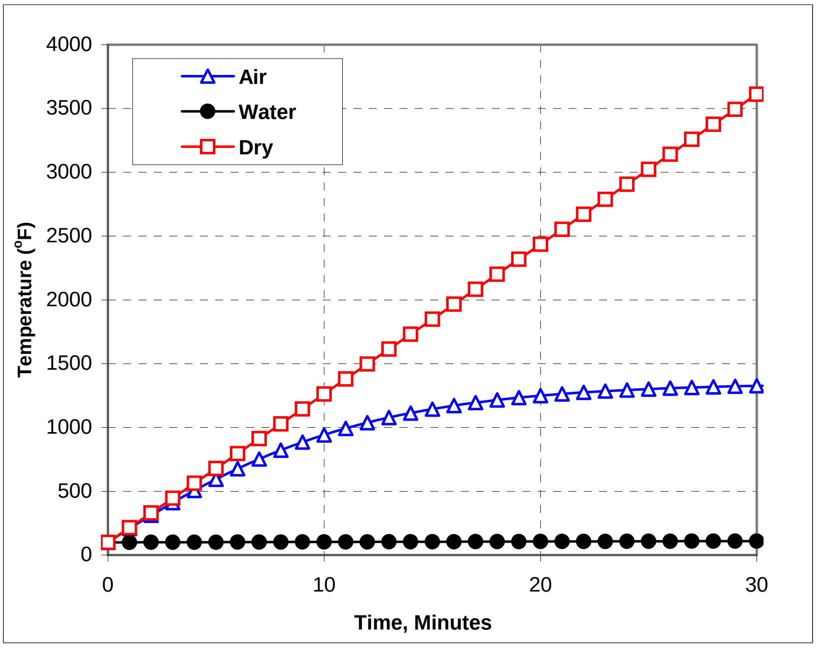

Figure 5 - Influence of different medium on bit temperature.

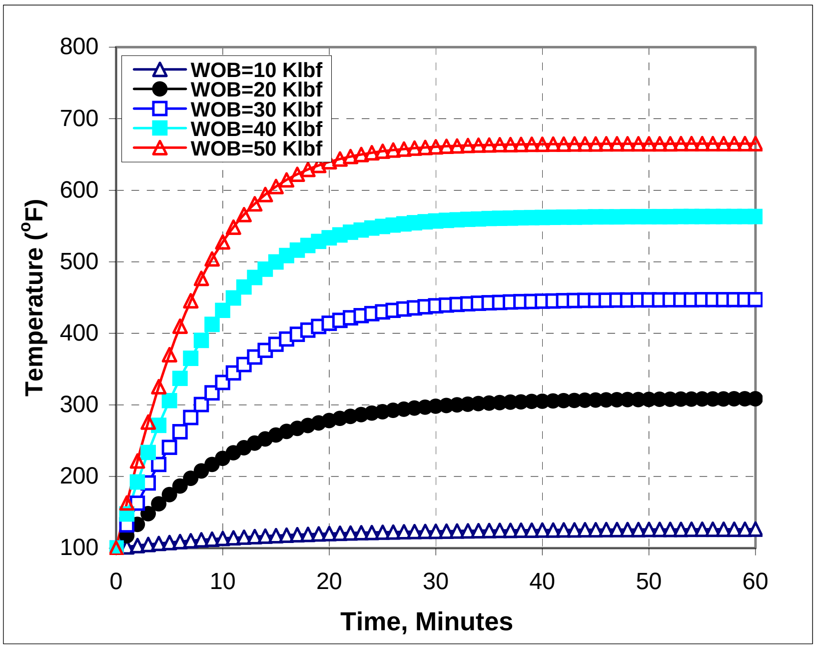

Figure 6 - Effects of weight on bit on bit temperature (Q=2000 SCFM and n=50 rpm).

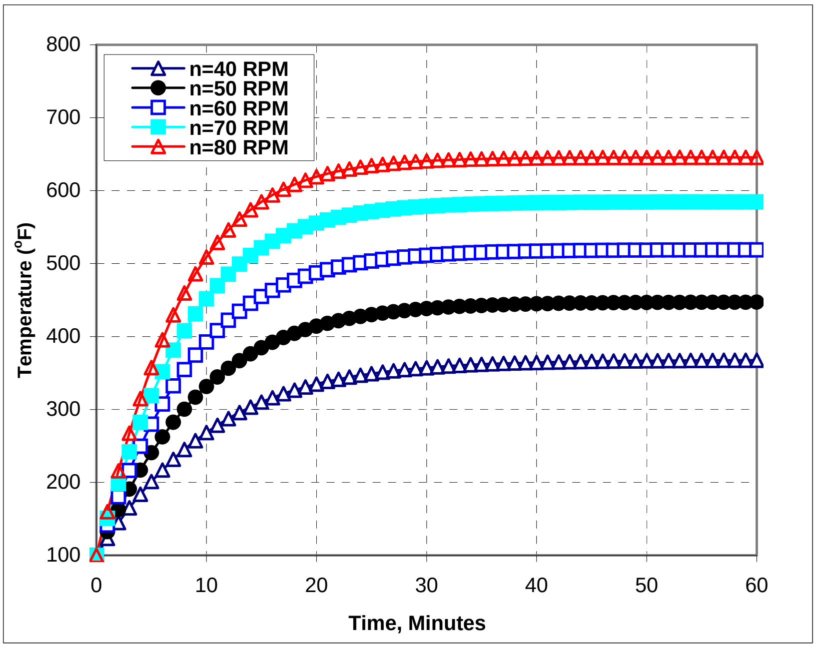

Figure 7 - Influence of rotary speed on bit temperature.

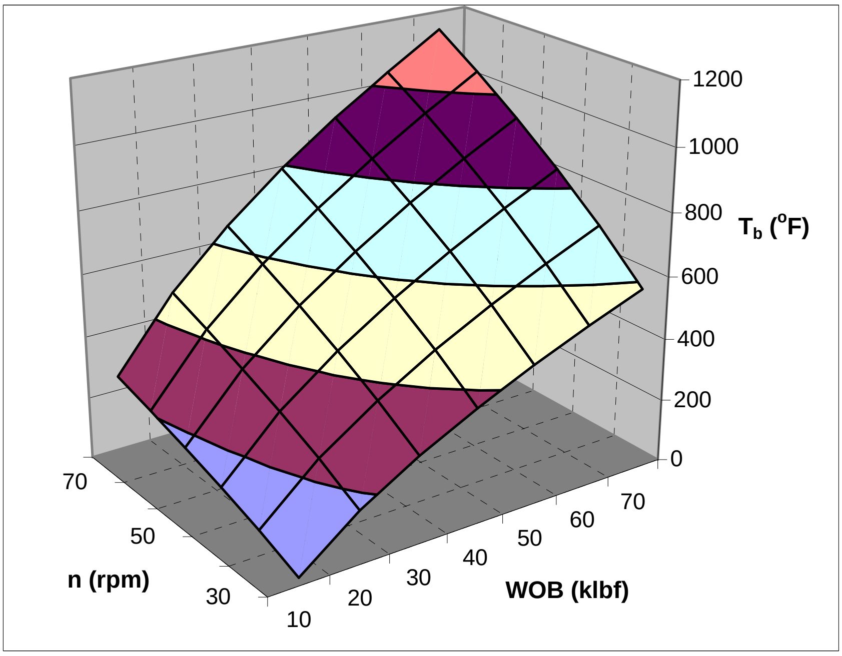

Figure 8 - Determination of weight on bit and rotary speed.

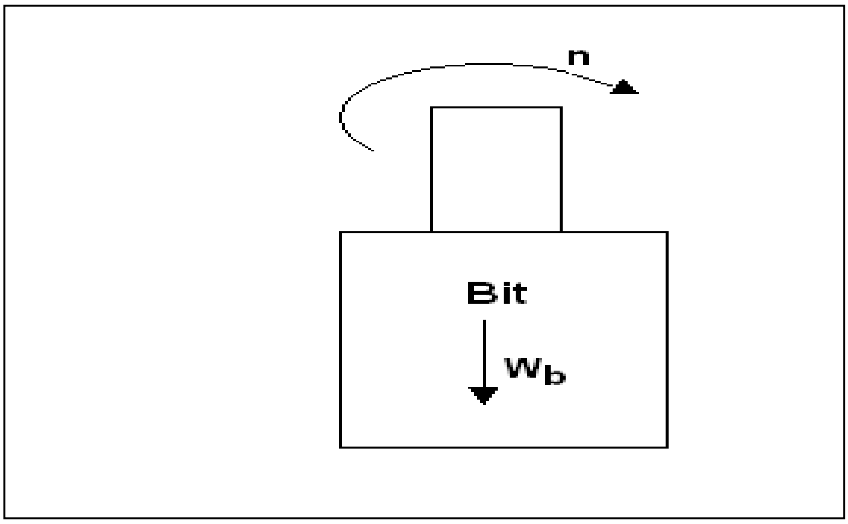

Figure A-1 – Frictional energy generated by the bit