Proceedings of ICFDP7:
Seventh International Congress on Fluid Dynamics and Propulsion
December 18-20, 2001, Cairo, Egypt

ICFDP7-2001010

ANALYSIS OF UNSTABLE BICOMPONENT COOLING LUBRICANT FLOW IN INLET ANNULAR CHANNELS OF THE BTA DRILLS IN THE PRESENCE OF DYNAMIC BREAKAGE AND COALESCENCE PROCESSES

Ashraf S. Ismail

Assistant Professor
Department of Engineering Mathematics and Physics,
Faculty of Engineering,
Alexandria University,
Alexandria 21544, Egypt

ABSTRACT

The unstable bicomponent oil-in-water (O/W) and water-in-oil (W/O) mixtures flow through the inlet annular channel of the BTA deep-hole drills, are studied in this paper. A mathematical model is developed taking account the turbulence modification of the continuous phase due to the presence of a dispersed phase. The population balance equation based on the breakage and coalescence models is used to generate the theoretical drop size distributions in bicomponent mixtures. The momentum, continuity, and population balance equations are solved numerically to calculate the holdup and pressure loss through the inlet annular channel of the BTA drill. The resultant effect of the breakage, coalescence and damping of turbulence decreases the pressure loss through the annular channel. The decrease of the pressure loss in the inlet annular channel will modify the cooling lubrication of the machining zone and increase the reliability of the cooling lubricant in carrying away the chips through the interior of the drill head and the boring bar. Also, the use of W/O and O/W mixtures as cooling lubricant will reduce the high share of the cooling lubricant costs from the total manufacturing costs.

NOMENCLATURE

$A(z,u)\,\delta u$	the number fraction of drops having volumes between u and $u+\delta u$ at position z.
d_{pmax}	maximum drop diameter (m)
d	drop diameter (m), $[d=(6u/\pi)^{1/3}]$
H	film thickness (m)
$h_{b,cb}(z,u)$	rate of drop generation by breakage and coalescence, respectively ($m^{-3}s^{-1}$)
$h_{b,cd}(z,u)$	rate of drop destruction by breakage and coalescence, respectively ($m^{-3}s^{-1}$)
f_r, f_s	turbulent friction factors at rotor and stator
K_x	dimensionless shear parameter, $=(K_r+K_s)/2$
K_r, K_s	turbulent shear parameters at rotor and stator surfaces
L	length of the inlet annular channel (m)
M	mass flow rate (kg/s)
N	the total number of drops per unit volume of dispersion.
P	pressure (N/m^2)
Pin	pressure at entrance (N/m2)
R, Db	boring bar radius and diameter (m)
Re_r	Reynolds number relative to rotor (boring bar)
Re_s	Reynolds number relative to stator (workpiece)
Reo	$\rho WH/\mu$, Reynolds number at the entrance of the inlet channel
RPM	boring bar RPM
r_s, r_r	mean surface roughness at workpiece (stator) and boring bar (rotor) (m)
W,U	mean flow axial and circumferential velocities (m/s)
x,y,z	$(0,\pi d_i)$, (0,H), (0,L), coordinates defining the flow region.
$\Phi(z)$	holdup
Φo	entrance holdup
σ	surface tension (N/m)
Ω	angular velocity of boring bar (1/s)
ρ	mixture density (kg/m^3)
μ	mixture viscosity (Ns/m^2)
ν	mixture kinematic viscosity (m^2/s)
ε	energy dissipation rate per unit mass (m^2/s^3)
τ_{xy}, τ_{zy}	shear stress in x and z directions (N/m^2), respectively.
$\tau_{xy}\vert^{H}$	shear stress on the boring bar surface (N/m^2)
u	drop volume (m^3)
u_{max}, u_{min}	maximum and minimum drop volumes in the dispersion (m)

Subscripts

c	continuous phase
d	dispersed phase
i	index defines the axial position
J, K	define the drop classes

INTRODUCTION

The deep-hole drilling processes are used to machine holes having a length-to-diameter ratio of more than ten.

Although expensive equipment is required, deep-hole drilling is being increasingly used for manufacturing operations where the holes have a lower length-to-diameter ratio because of its high productivity and the hole quality that can be achieved [1]. Due to its excellent machining performance, deep hole drillings are often applied in high precision manufacturing such as the military industry, machine tool and automobile industries [2].

The BTA system is the ideal system for drilling very deep holes because it is rigid and is capable of delivering enough pressurized cooling lubricant to the cutting edge regardless of the bore depth. In the BTA system, Fig. 1, the boring bar is threaded to the drilling tool. The system incorporates a pressure head to pump cooling lubricant through the annular channel between the boring bar and the bore wall toward the drill head. After cooling and lubricating the machining zone, the cooling lubricant carries away the chips through the interior of the drill head and the boring bar. Under optimal drilling conditions, the returning chips do not come into contact with the bore wall thus an excellent bore finish is obtained [3]. One of the main problems associated with deep-hole drilling is chip removal from the machining zone. To overcome this problem the machining zone is flooded with the cutting fluid under high pressure. However, this does not always solve the problem of high energy losses that take place in the hydraulic systems of these drills, which result in a significant drop in the cutting fluid pressure [4]. Astakhov et al. [3-6] conducted their study to increase the effectiveness of the deep hole drilling process.

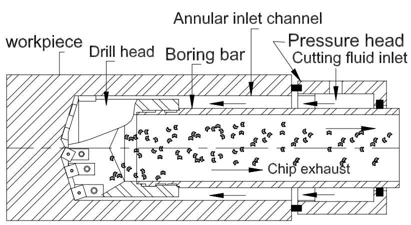


Fig. 1 BTA deep-hole drilling process.

The type of cooling lubricant and its supply have a great influence on cutting processes. Component quality and tool wear, depend on the cooling lubricating conditions. On the other hand, it is pointed out that cooling lubricants represent a significant part of the manufacturing costs, and have to be taken into account when examining economics in machining [7].

Oil-in-water (O/W), with water as the continuous phase, is employed as cutting fluid, in metal machining, under circumstances where the high heat capacity of water is beneficial while the rather poor lubricating properties of an O/W emulsion are acceptable. If the rather small viscosity of this emulsion is inadequate for the application yet fire resistance is required, the water-in-oil (W/O) emulsion where the oil is the continuous phase, is often employed [8]. Rajinder Pal [9] observed that in the turbulent regime, the friction factors for the unstable emulsions fall somewhat below those of the stable emulsions. The difference also increases with the increase in the dispersed phase concentration. He explained that this observation is consistent with the proposed mechanism that the turbulence of the carrier fluid of the emulsions (continuous phase) is modified in the presence of dynamic coalescence and breakup processes. The unstable W/O emulsions exhibit much stronger drag reduction activity than the unstable O/W emulsions.

Thus, because of the good lubricating ability, excellent cooling efficiency, nonflammability, low cost, and drag reduction activity under turbulent flow conditions, of the W/O and O/W mixtures, they are used as cooling lubricant in the present analysis. A mathematical model is proposed, taking account breakage and coalescence of drops, and damping of turbulence due to the presence of dispersed phase, to study their effects in modifying the pressure loss in the inlet annular channel.

POPULATION BALANCE MODEL

In the dispersed phase system, the material domain comprises a continuous phase and a dispersed phase, the latter as a population of drops in which the identities of individuals are continually destroyed and recreated by breakup and coalescence processes. The spread of drop sizes affects the hydrodynamic behavior of the system, modeling based solely on the mean drop diameter and neglect coalescence and breakup is not very accurate [10]. Several factors affect the processes of breakage and coalescence and determine whether the two processes or one of them should be taking place. For example in the region of flow where the energy dissipation is very high or the case of adding surfactant to the dispersion, the breakage process will dominate the coalescence process. For the region of low energy dissipation rate or the case of suddenly decreasing the rate of energy dissipation, the coalescence processes will be dominant [11].

Considering the control volume in Fig. 2, the population balance model is based on an equation for the continuity of drop numbers in a dispersed phase and is developed from the general conservation equation [12].

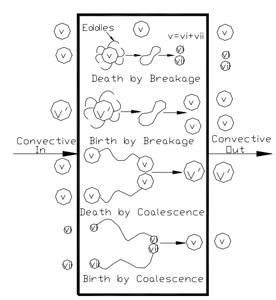


Fig. 2 Control volume

For steady state, the population balance equation (PBE) can be written as:

$$\frac{d\,[W\,N\,A(z,u)]}{dz} = h_{bb} - h_{bd} + h_{cb} - h_{cd} \qquad (1)$$

h_{bb} is the rate of production function of drops of state (z,u) by breakage of other drops of state (z,u'), which can be represented by [13]:

$$h_{bb} = \int_{u}^{u_{max}} (1-\Phi(z))\, N\, A(z,u')\, C_4\, (\varepsilon/d'^2)^{1/3} \int_{\xi_{min}}^{1} \frac{(1+\xi)^2}{\xi^{11/3}} \exp\left(-\frac{12\, C_f\, \sigma}{\beta\, \rho_c\, \varepsilon^{2/3}\, d'^{5/3}\, \xi^{11/3}}\right) \delta\xi\, \delta u' \quad (2)$$

where $\Phi(z)$ is the local holdup of the dispersed phase,

$$\Phi(z) = \int_{u_{min}}^{u_{max}} N\, A(z,u)\, u\, \delta u \,/(\text{volume of space element}) \quad (3)$$

ε is the energy dissipation rate per unit mass. From the energy transport equation for two-phase flow [14], ε can be written as:

$$\varepsilon = \frac{R\, \Omega\, \tau_{xy}\big|^{H} - U\, \tau_{xy}\big|_0^{H} - W\, \tau_{yz}\big|_0^{H}}{\rho\, H} \quad (4)$$

The wall shear stresses are calculated according to the bulk flow theory for turbulence in thin film flows [14]:

$$\tau_{xy}\big|_0^{H} = \frac{\mu}{H}\left(K_x\, U - K_r \frac{R\, \Omega}{2}\right) \quad (5)$$

$$\tau_{zy}\big|_0^{H} = -\frac{\mu\, (K_r + K_s)}{2\, H}\, W \quad (6)$$

$$\tau_{xy}\big|^{H} = \frac{\mu}{4\, H}\left\{ U\, K_s - (U - R\, \Omega)\, K_r \right\} \quad (7)$$

The parameters $K_{r,s}$ are defined in Eq.(26)The lower limit $\xi_{min} = l_{min}/d$, where l_{min} is the minimum size of eddies in the inertial subrange of isotropic turbulence,

$$l_{min}/l_d \approx 11.4\text{-}31.4 \quad (8)$$

l_d is the Kolmogrov microscale [15],

$$l_d = (\nu^3/\varepsilon)^{1/4}$$
(9)

h_{bd} is the rate of death function of drops of state (z,u) by breakage which can be represented by [13]:

$$h_{bd} = 0.5 \int_{0}^{1} (1-\Phi(z))\, N\, A(z,u)\, C_4\, (\varepsilon/d^2)^{1/3} \int_{\xi_{min}}^{1} \frac{(1+\xi)^2}{\xi^{11/3}} \exp\left(-\frac{12\, C_f\, \sigma}{\beta\, \rho_c\, \varepsilon^{2/3}\, d^{5/3}\, \xi^{11/3}}\right) \delta\xi\, \delta f_{BV} \quad (10)$$

For binary breakage, a drop of size u or d breaks into two drops sizes of $u f_{BV}$ and $u(1-f_{BV})$, where f_{BV} can be defined as:

$$f_{BV} = \frac{u_i}{u} = \frac{u_i}{u_i + u_{ii}} \quad (11)$$

where u_i and u_{ii} are volumes of daughter drops in binary breakage of a parent drop with volume u.
C_f is a function of f_{BV}, that is

$$C_f = f_{BV}^{2/3} + (1-f_{BV})^{2/3} - 1 \quad (12)$$

The constants C_4=0.923, and β=2.04. The birth rate, $h_{cb}(z,u)$, and death rate, $h_{cd}(z,u)$, by coalescence of drops of state (z,u), are expressed as [16]:

$$h_{cb} = \int_{0}^{u/2} \lambda(u-u', u')\, \omega(u-u', u')\, NA(z, u-u')\, NA(z, u')\, du' \quad (13)$$

$$h_{cd} = NA(z, u) \int_{0}^{u_{max}-u} \lambda(u, u')\, \omega(u, u')\, NA(z, u')\, du' \quad (14)$$

Here, $\lambda(u, u')$ is the coalescence efficiency between drops of size u and u', and $\omega(u, u')$ is the collision frequency between drops of size u and u'. In turbulent dispersions, the collisions may result from the random motion of drops due to turbulence. For coalescence of droplets to occur in a turbulent flow field the droplets must first collide and then remain in contact for sufficient time so that the processes of film drainage, film rupture and coalescence may occur. During these processes a turbulent eddy may separate the droplets and prevent coalescence. The binary collision frequency between drops of volume u and u' is derived by assuming that the mechanism of collision in a locally isotropic flow field is analogous to collisions between molecules as in the kinetic theory of gases. Accordingly [16]:

$$\omega(u, u') = C_{III}\, (u^{2/3} + u'^{2/3})(u^{2/9} + u'^{2/9})^{1/2}\, \varepsilon^{1/3} \quad (15)$$

The coalescence efficiency $\lambda(u, u')$ is defined as the fraction of collisions between drops of size u, and u' that result in coalescence. The coalescence efficiency is written in terms of drop volumes as [16]:

$$\lambda(u, u') = \exp\left[-\frac{C_{IV}\, \mu_c\, \rho_c\, \varepsilon}{\sigma^2}\left(\frac{u^{1/3}\, u'^{1/3}}{u^{1/3} + u'^{1/3}}\right)^{1/2}\right] \quad (16)$$

The constants C_{III}=1.5E-4, and C_{IV}=1.83E+9. Solution of the resulting population balance equation, enables prediction of drop size distribution. The dispersion density and viscosity are expressed as functions in the local holdup:

$$\rho(z)= \rho_d \, \Phi(z)+(1-\Phi(z)) \, \rho_c \qquad (17)$$

$$\mu(z)=\mu_c \left\{1+2 \, \Phi(z) \left[\frac{0.4+ (\mu_d/\mu_c)}{1+ (\mu_d/\mu_c)}\right]\right\} \qquad (18)$$

The factor multiplying $\Phi(z)$, in Eq.(18), varies only from 2.5 to 1.75 over a wide range of (μ_d/μ_c) from 0 to unity [9].

TURBULENCE MODULATION BY DISPERSED PHASE AND BULK FLOW GOVERNING EQUATIONS

It has been reported in the literature [16] that experiments on two-phase jet flows show that the "damping" of turbulence can be approximated by correlation between mean square velocity fluctuation in turbulence jets in the presence and absence of dispersed phase:

$$u'^2= \frac{u_o'^2}{(1+4 \, \Phi(z))^2} \qquad (19)$$

Thus, in the present analysis, the turbulent stresses are multiplied by a function γ to take into account the damping effect on turbulence by the dispersed phase.

$$\tau(\text{damped})= \gamma \, \tau(\text{undamped}) \qquad (20)$$

$$\text{where } \gamma = 1/(1+4 \, \Phi(z))^2 \qquad (21)$$

The turbulent bulk-flow of variable properties is described by the continuity and momentum equations given as [14]:

Continuity:

$$M =2 \, \pi R \, H \, \rho \, W = \text{Constant} \qquad (22)$$

Circumferential Momentum:

$$\tau_{xy} \big|_0^H = \frac{\mu}{H}\left(K_x U - K_r \frac{R \, \Omega}{2}\right) =0 \qquad (23)$$

Rearrange Eq.(23) to obtain

$$U= \frac{K_r R \, \Omega}{2 \, K_x} \qquad (24)$$

Axial Momentum:

$$\frac{d(\rho H W^2)}{dz}= - H \frac{dP}{dz} + \gamma \, \tau_{zy} \big|_0^H \qquad (25)$$

where

$$K_r=f_r \, Re_r$$

$$K_s=f_s \, Re_s$$

$$f_r= a_m \left\{1 + \left(\frac{C_m \, r_r}{H} + \frac{b_m}{Re_r} \right)^e \right\}$$

$$f_s= a_m \left\{1 + \left(\frac{C_m \, r_s}{H} + \frac{b_m}{Re_s} \right)^e \right\}$$

a_m=0.001375 ; b_m= 5×10^5, C_m= 10^4, e= 1/3

$$Re_r= \rho \, H \, \{(U-\Omega \, R)^2 + W^2 \}^{0.5} /\mu$$

$$Re_s= \rho \, H \, \{U^2 + W^2 \}^{0.5} /\mu \qquad (26)$$

NUMERICAL ANALYSIS

The population balance equations (PBE) are solved numerically using finite difference method [17], Simpson's integration technique [18], or fourth-order Runge-Kutta method [19]. AlTaweel et al.[20] and Polprasert et al. [21] concluded that high accuracy in solving population balance equations was achieved by using an algorithm that reduces the error resulting from discretization in the drop size domain (e.g. cubic Spline interpolation), and maintains optimum drop size integration range and the number of intervals used to describe the population.

In the present analysis, the domain of the governing equations is divided into 10 divisions in the axial direction, and a number of drop classes equal 40. As shown in Fig. 3, the intervals are numbered consecutively from small to large sizes with interval J containing drops larger than υ_{J-1} and smaller than or equal to υ_J. The class J is represented by the mean value between υ_J and υ_{J-1}.

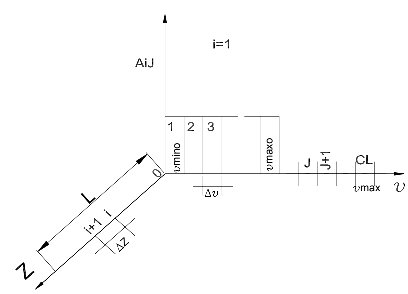


Fig. 3 Numbering system for discretized intervals.

A second-order approximation (macromixing), tanks in series model Fig. 4, is used to describe the flow pattern in the bicomponent system [22]. Each stage considered as constant flow stirred tank system (CFSTS) and, as its name suggest, it is a system in which the contents are well stirred (hydrodynamically due to turbulence in our case) and uniform throughout. Thus, the exit stream from this system has the same holdup as the mixture within the tank.

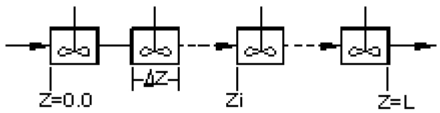


Fig. 4 Tanks in series model.

Eq. 1 is written as follows:

$$W_i \; N_i \, A_{iJ} = W_{i-1} \, N_{i-1} \, A_{i-1,J} + \Delta z \, \{ \sum_{K=J+1}^{CL} (1-\Phi_i) \, N_i \, A_{iK} \, C_4 \, (\varepsilon_i/d_K^2)^{1/3} \, I_{ik} \, \Delta u - 0.5 \, (1-\Phi_i) \, N_i \, A_{iJ} \, C_4 \, (\varepsilon_i/d_J^2)^{1/3} \sum_{m=1}^{J-1} I_{im} \, \Delta f_{BV} \} + \Delta z \, \{ \sum_{K=1}^{J/2} \lambda_{J-k,k} \, \omega_{J-k,k} \, N_i \, A_{i,J-k} \, N_i \, A_{i,k} \, \Delta u - N_i \, A_{i,J} \sum_{K=1}^{CL-J} \lambda_{J,k} \, \omega_{J,k} \, N_i \, A_{i,k} \, \Delta u \} \qquad (27)$$

, where

$$I_{ik} = \int_{\xi_{min}}^{1} \frac{(1+\xi)^2}{\xi^{11/3}} \exp\left(-\frac{12 \, C_{fK} \, \sigma}{\beta \, \rho_c \, \varepsilon_i^{2/3} \, d_K^{5/3} \, \xi^{11/3}}\right) \delta\xi \qquad (28)$$

$\xi_{min} = \lambda_{min}/d_K$

$$C_{fK} = \left(\frac{u_J}{u_K}\right)^{2/3} + \left(1 - \frac{u_J}{u_K}\right)^{2/3} - 1 \qquad (29)$$

, and

$$I_{im} = \int_{\xi_{min}}^{1} \frac{(1+\xi)^2}{\xi^{11/3}} \exp\left(-\frac{12 \, C_{fm} \, \sigma}{\beta \, \rho_c \, \varepsilon_i^{2/3} \, d_J^{5/3} \, \xi^{11/3}}\right) \delta\xi \qquad (30)$$

$\xi_{min} = \lambda_{min}/d_J$

$$C_{fm} = \left(\frac{u_m}{u_J}\right)^{2/3} + \left(1 - \frac{u_m}{u_J}\right)^{2/3} - 1 \qquad (31)$$

The integrals I_{ik} and I_{im} are determined numerically using trapezoidal rule. The drop size distribution at the inlet is assumed uniform:

$$A(0,u) = \frac{1}{u_{maxo} - u_{mino}} \qquad (32)$$

Where u_{maxo} and u_{mino} are the maximum and minimum drop volumes, respectively, at the entrance of the inlet channel.
The axial velocity W is calculated from the continuity equation. The pressure distribution is calculated from the axial momentum equation, which can be written as:

$$P_i = P_{i-1} + \frac{\Delta z}{H} \left[\gamma \, \tau_{zy}|_o^H - \frac{d}{dz}(\rho H W^2) \right]_i \qquad (33)$$

The flow chart in Fig. 5 describes the iterative solution steps.

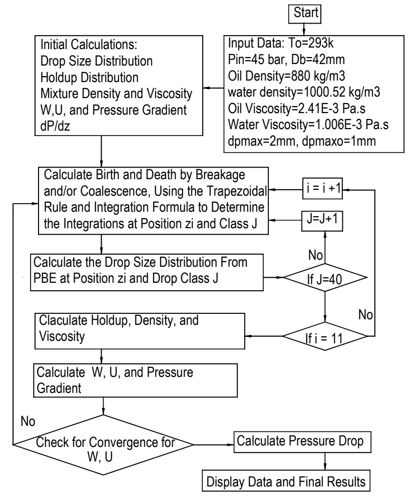


Fig. 5 Flow Chart.

HOLDUP RISE AND PRESSURE LOSS

The breakage of drops increases the holdup. This could be explained by considering one stage from the CFSTS model, Fig. 6, for example, if drop of diameter d entered at the inlet area and breaks inside the tank into two equal drops each of diameter d'. The diameter d' ≈ 0.8 d. The two drops exit at the exit area of the tank. This means that the dispersed phase area over the exit area (holdup) is higher than the one at the inlet area. The coalescence of drops decreases the holdup and could be explained in the same way.

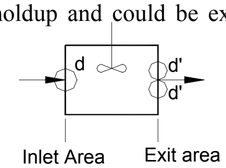


Fig. 6 One stage of CFSTS model.

The holdup rise represents the difference between the holdup at the outlet and inlet sections of the annular channel. From Eq.(4), as the Reynolds number increase, RPM increase, and clearance decrease, the energy dissipation rate per unit mass, ε, increase. From the breakage rate model Eqs.(2, 10), it is obvious that as ε increases, the breakage rate increase, i.e., the holdup increase. The coalescence rate depends on the collision rate and the coalescence efficiency. It is obvious from Eqs.(15, 16) that the coalescence rate depends on the energy dissipation rate and size of colliding drops. As the drops size (u, u'), and energy dissipation rate increase, the coalescence rate decrease.
In Figs. (7-10), as the energy dissipation rate (ε) increase, the holdup rise increase due to the breakage process. In the O/W mixture, the coalescence process becomes dominant as the energy dissipation rate decrease. Thus, for Reo less than 5000, the holdup decrease through the inlet annular channel. The breakage rate of the water drops in the W/O mixture is higher than that for oil drops in the O/W mixture. Thus, the holdup rise for W/O is greater than that for O/W.

The pressure loss through the inlet annular channel is the difference between pressure at the outlet and inlet sections of the annular channel. In Figs. (11,13), compare the case of considering breakage, coalescence and damping of turbulence, with the case of neglecting these processes for W/O and O/W mixtures. It is clear that as Reo increase, H decrease, L increase, and Φo increase, the difference between the two cases also increase. A comparison between three cases is shown. The first case neglects breakage, coalescence, and damping of turbulence. The second case neglects breakage and coalescence, and considers damping of turbulence only. The third case considers the breakage, coalescence, and damping of turbulence. It is clear that as Reo increase, the breakage becomes dominant, and the pressure loss is slightly decrease. As Reo decrease, the coalescence becomes dominant, and pressure loss is slightly increase. For the case of neglecting damping of turbulence, as Φo increase, the viscosity of the mixture increase leading to increase in the pressure loss. Considering the damping of turbulence effect, as Φo increase, the pressure loss decrease. In Fig.14, the RPM has very small effect on the pressure loss.

It is clear that the main process that significantly affects the pressure loss, in both W/O and O/W mixtures, is the damping of turbulence due to the presence of dispersed phase.

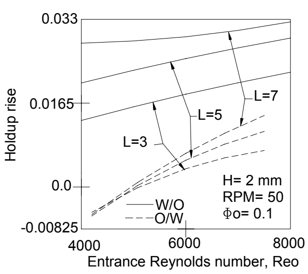


Fig. 7 Effect of Reo on holdup rise.

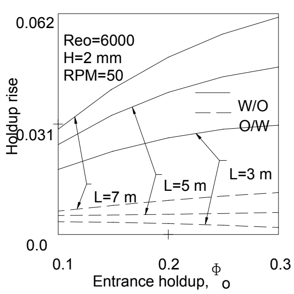


Fig. 8 Effect of ϕ_o on holdup rise.

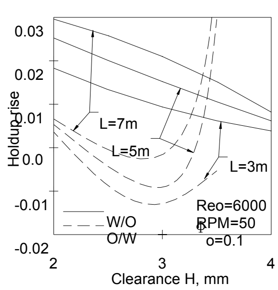


Fig. 9 Effect of H on holdup rise.

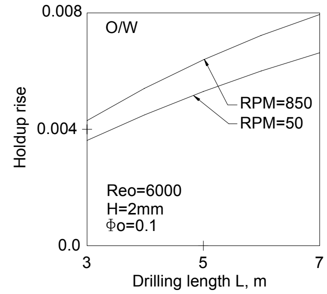
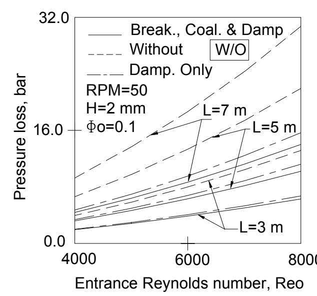


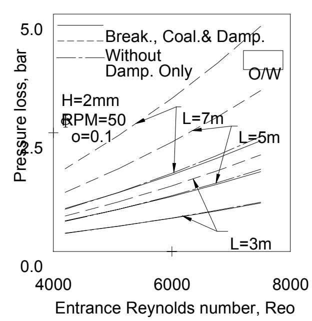
Fig. 10 Effect of RPM on holdup rise.

CONCLUSIONS

The resultant effect, of breakage, coalescence and damping of turbulence, decrease the pressure loss for W/O and O/W mixtures. The decrease of the pressure loss in the inlet annular channel will modify the cooling lubrication of the machining zone and increase the reliability of the cooling lubricant in carrying away the chips through the interior of the drill head and the boring bar. In addition, since cooling lubricants represent a significant part of the manufacturing cost, the use of W/O and O/W mixtures reduce these costs.

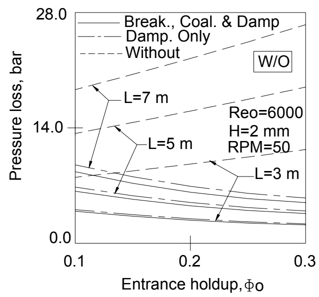


(a)W/O

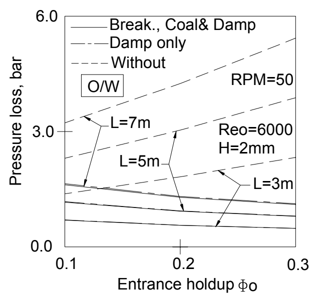


(b) O/W

Fig. 11 Effect of Reo on pressure loss.

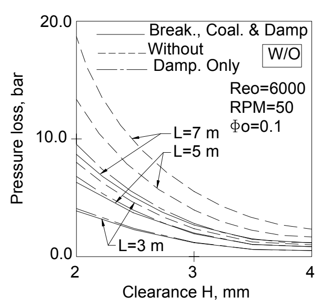


(a) W/O

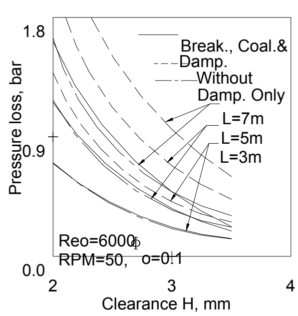


(b) O/W

Fig. 12 Effect of entrance holdup on pressure loss.



(a) W/O



(b) O/W

Fig. 13 Effect of clearance H on pressure loss.

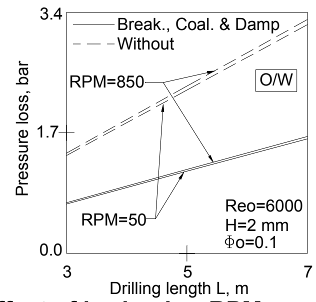


Fig. 14 Effect of boring bar RPM on pressure loss.

REFERENCES

[1] Weinert, K., and Bruchhaus, T., 1999, ”Tribological Investigations into the Operational Behavior of Self-Piloting Drilling Tools”, Wear, 225-229, pp. 925-935.

[2] Chin, J., Hsieh, C., and Lee, L., 1996, ”The Shaft Behavior of BTA Deep Hole Drilling Tool”, Int. J. Mech. Sci., vol. 38, No. 5, pp. 461-482.

[3] Astakhov, V.P., Subramanya, P.S. and Osman, M.O.M., 1995, ” An investigation of the cutting fluid flow in self-piloting drills,” Int. J. Mach. Tools Manufact., Vol. 35(4), pp. 547-563.

[4] Astakhov, V.P., Subramanya, P.S., and Osman, M.O.M. , 1996, ”On The Design of Ejectors for Deep Hole Machining,” Int. J. Mach. Tools Manufact., vol.36, No.2, pp. 155-171.

[5] Astakhov, V.P., Subramanya, P.S., and Osman, M.O.M., 1995, ” Theoretical and experimental investigations of coolant flow in inlet channels of the BTA and ejector drills”, Proc. Instn. Mech. Engrs., Part B: Journal of Engineering Manufacture, vol. 209, pp. 211-220.

[6] Astakhov, V.P., Abi Karam, S., and Osman, M.O.M., 1998, ”The Correlation Between the Cutting Fluid Distribution and the Topography of Tool Wear in BTA Drilling”, ASME Journal of Manufacturing Science and Engineering, Vol. 120, pp. 820-822.

[7] Brinksmeier, E., Walter, A., Janssen, R., and Diersen, 1999, “Aspects of Cooling Lubrication reduction in machining advanced materials,” Proc. Instn. Mech. Engrs., vol. 213, part B, pp. 769-778.

[8] Al-Sharif, A., Chamniprasart, K., Rajagopal, K.R., and Szeri, A.Z., 1993, ”Lubrication With Binary Mixtures: Liquid-Liquid Emulsion”, ASME Journal of Tribology, Vol. 115, pp. 46-55.

[9] Rajinder Pal, 1993, ” Pipeline Flow of Unstable and Surfactant-Stabilized Emulsions”, AIChE Journal, vol. 39, No.11, pp.1754-1764.

[10] Laso, M., Steiner, L., and Hartland, S., 1987, ”Dynamic Simulation of Liquid-Liquid Agitated Dispersions- I. Derivation of a Simplified Model”, Chemical Engineering Science,vol.42,No.10,pp.2429-2436.

[11] Tsouris, C., and Tavlarides, L.L., 1994, ” Breakage and Coalescence Models for Drops in Turbulent Dispersions”, AIChE Journal, vol. 40, No. 3, pp. 395-406.

[12] Ramkrishna, D., 1985, ” The Status of Population Balances”, Reviews in Chemical Engineering”, vol. 3, No.1, pp. 49-95.

[13] Hean Luo, and Svendsen, H. F., 1996, ” Theoretical Model for Drop and Bubble Breakup in Turbulent Dispersions,” AIChE Journal, Vol. 42(5), pp. 1225-1233.

[14] Arauz, G. L. and San Andres, L., 1998, " Analysis of Two-Phase Flow inCryogenic Damper Seals-Part I: Theoretical Model,"ASME Journal of Tribology, Vol. 120, pp. 221-227.
[15] Kawase, Y., and Moo-Young, M., 1990, " Mathematical Models for Design of Bioreactors: Applications of Kolmogoroff's Theory of Isotropic Turbulence", The Chemical Engineering Journal, Vol. 43, pp. B19-B41.
[16] Coulaloglou, C.A., and Tavlarides L.L., 1977, " Description of Interaction Processes in Agitated Liquid-Liquid Dispersions," Chemical Engineering Science, Vol. 32, pp. 1289-1297.
[17] Mihail, R., and Straja, S., 1986, "a Theoretical Model Concerning Bubble Size Distributions", Chem. Eng. J., vol. 33, pp. 71-77.
[18] Lee, Chung-Hur, Erickson, L.E., and Glasgow, L.A., 1987, "Dynamics of Bubble Size Distribution in Turbulent Gas-Liquid Dispersions", Chem. Eng. Comm., vol. 61, pp. 181-195.
[19] Niyogi, D., Kumar, R., and Gandhi, K.S., 1992, "Modelling of Bubble Size Distribution in Free Rise Polyurethane Foams", AIChE Journal, vol. 38, No. 8, pp. 1170-1184.
[20] AlTaweel, A.M., Webber, J.R., Devavarapu, R.C., Elsayed, A.S., and Gupta, Y.P., 1997, "An Algorithm for Accurately Solving Population Balance Problems", Presented at the 47th Canadian Chem. Engineering Conference, Edmonton, October.
[21] Polprasert, G., AlTaweel, A.M., Webber, J.R., Devavarapu, R.C., Elsayed, A.S.I., Gupta, P., Prabriputaloong, K., and Tangsatitkulchai, C., 1998, "Factors Affecting the Accuracy of Population Balance Solutions in Immiscible Systems", Presented at the 1998 AIChE National Conference, Miami Beach FL, Nov. 1998.
[22] Himmelblau, D.M., and Bischoff, K.B., 1968, "Process Analysis and Simulation: Deterministic Systems", John Wiley&Sons Inc., p.191.