Effect of Shear Heat on Hydrodynamic Lift of Brush Seals in Oil Sealing

E. Tolga Duran[1] and Mahmut F. Aksit[2]
Sabanci University, Istanbul, Turkey,34956

Importance of hydrodynamic lift clearance has been stated in previous studies [1, 2, 3]. At those studies, derivation of closed form function for oil temperature has been performed and the shear heat dissipation effect has been successfully integrated into the lift force formulation. Oil pressure is successfully derived by tracking three different ways, all of which give very similar results to each other. All these analyses are advanced fluid mechanics and heat transfer analyses, which give consistent results with real-life applications. In this study, function of shear heating effect included in hydrodynamic lift clearance formulation. For a different pressure loads (which is a design parameter and known), change of hydrodynamic lift clearance with rotor surface speed can be found without requiring any experimental leakage data. Furthermore, theoretic lift clearance has consistency with the experimental lift data.

Theoretic Hydrodynamic Lift Clearance

Idea of deriving hydrodynamic lift clearance arises from the almost linear oil pressure. Although oil pressure under each bristle, which is given in Duran et al. [3] is found as a complicated function of lift clearance, pressure load, rotor surface, effective viscosity, bristle geometry and local coordinates, it gives almost linear pressure distribution along rotor axial direction as mentioned in [3]. Difference between the linear oil pressure of Duran et al. [1] and [3] for the i^{th} bristle is defined as error function.

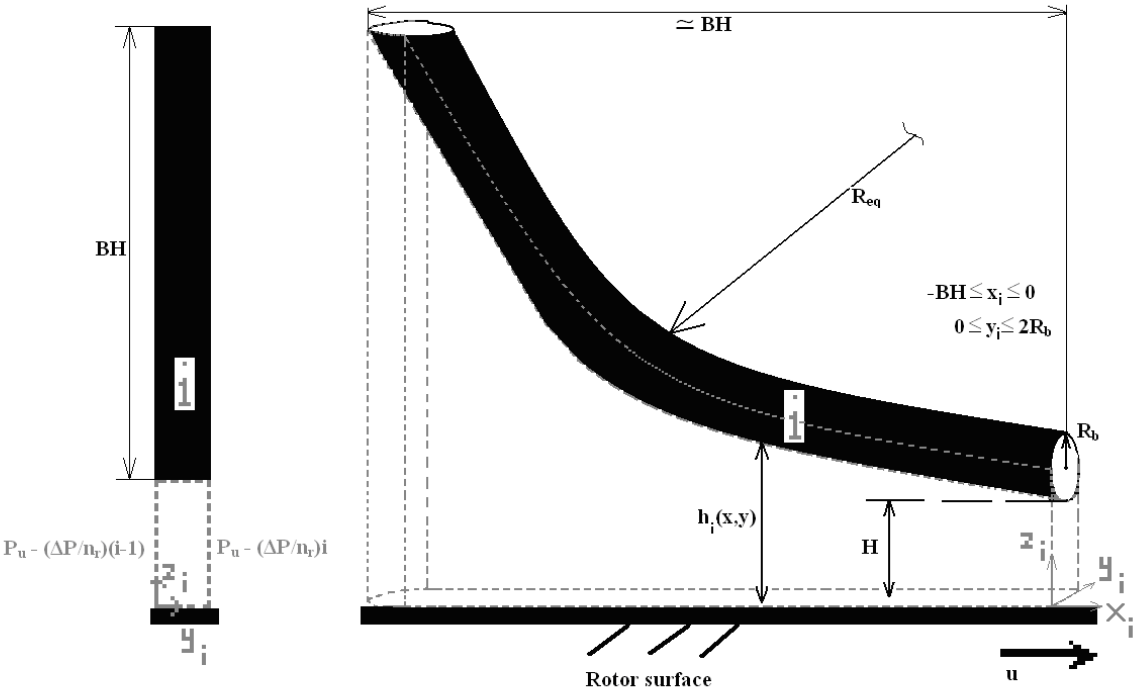

Figure 1 Geometry, local coordinate selection and boundaries for i^{th} bristle

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[1] PhD student, Faculty of Eng. and Natural Sci., Sabanci University, Istanbul etolgaduran@su.sabanciuniv.edu, Student member

[2] Assoc. Prof., Faculty of Eng. and Natural Sci., Sabanci University, Istanbul, aksit@sabanciuniv.edu, Member

$$\varepsilon_i(u,\Delta P,x_i,y_i)=P_{i-lin}-P_i \tag{1}$$

where

$$P_{i-lin}=P_u-\frac{\Delta P}{n_r}\cdot(i-1)-\frac{\Delta P}{2\cdot R_b\cdot n_r}\cdot y_i$$

and

$$P_i=F_3+\frac{F_2}{F_1}\cdot F_4+F_5\ ,$$

$$F_1=\frac{2R_b{}^3}{\left(\alpha_i^2\right)}\left\{\frac{2R_b}{\left(\alpha_i^2+4R_b{}^2\right)^2}+\frac{3}{2\alpha_i^2}\left[\frac{2R_b}{\alpha_i^2+4R_b{}^2}+\frac{1}{\alpha_i}\arctan\left(\frac{2R_b}{\alpha_i}\right)\right]\right\}$$

$$F_2=\frac{-\Delta P}{n_r}-\frac{6\mu_{eff}u}{R_{eq}}x_i\left(\frac{R_b}{2}\right)\left[\frac{1}{\left(H+\dfrac{x_i^2}{2R_{eq}}+1\right)^2}-\frac{1}{\left(H+\dfrac{x_i^2}{2R_{eq}}\right)^2}\right]\ ,$$

$$F_3=\frac{6\mu_{eff}\cdot u\cdot x_i}{R_{eq}}\cdot\left(\frac{-R_b}{2}\right)\cdot\frac{1}{\left(H+\dfrac{x_i^2}{2R_{eq}}+\dfrac{y_i^2}{2R_b}\right)^2}\ ,$$

$$F_4=\frac{2R_b{}^3}{\left(\alpha_i^2\right)}\left\{\frac{2R_b}{\left(\alpha_i^2+y_i^2\right)^2}+\frac{3}{2\alpha_i^2}\left[\frac{2R_b}{\alpha_i^2+y_i^2}+\frac{1}{\alpha_i}\arctan\left(\frac{y_i}{\alpha_i}\right)\right]\right\}\ ,$$

$$F_5=P_u-\frac{\Delta P}{n_r}\cdot(i-1)-\frac{6\mu_{eff}u}{R_{eq}}x_i\left[\frac{-R_b}{2}\cdot\frac{1}{\left(H+\dfrac{x_i^2}{2R_{eq}}\right)^2}\right]\ ,$$

$$\alpha_i^2=2R_b\cdot\left(H+\frac{x_i^2}{2R_{eq}}\right).$$

P_{i-lin} gives the linear pressure distribution along rotor axial direction for each bristle. Note that error function of Equation (1), $\varepsilon_i(u,\Delta P,x_i,y_i)$, depends on rotor surface speed and pressure load. In the study of Duran et. al [3], it has been mentioned that hydrodynamic lift clearance is assumed to be same for each bristle in a row of rotor axial direction. Therefore, derivation of lift clearance for any bristle gives the lift data for the brush seal. For this reason, values of error function for the last bristle, which corresponds to 16th bristle since n_r is sixteen, are evaluated for $x_{16} = -BH$ and $y_{16} = R_b/10000$.

Since there are two pressure load and three rotor surface speed data, the error function can be found as second degree polynomial of rotor surface speed and first degree polynomial of pressure load.

$$\begin{bmatrix} A \\ B \\ C \\ D \\ E \\ F \end{bmatrix} = \begin{bmatrix} 0.00000000871259 \\ -0.00138211964675 \\ -0.00000016864155 \\ 0.05703112974953 \\ 0.00000077084728 \\ -0.12156751681664 \end{bmatrix} \tag{2}$$

$$\begin{aligned} \varepsilon_{16}(u, \Delta P, x_{16} = -BH, y_{16} = R_b/10000) &= A \cdot u^2 \cdot \Delta P + B \cdot u^2 + C \cdot u \cdot \Delta P + D \cdot u + E \cdot \Delta P + F \\ &= P_{16-lin}(-BH, R_b/10000) - P_{16}(-BH, R_b/10000) \end{aligned}$$

where $x_i = -BH,\ y_i = R_b/10000,\ i = 16$

$$P_{i-lin} = P_u - \frac{\Delta P}{n_r} \cdot (i-1) - \frac{\Delta P}{2 \cdot R_b \cdot n_r} \cdot y_i$$

$$P_i = F_3 + \frac{F_2}{F_1} \cdot F_4 + F_5 \ ,$$

$$F_1 = \frac{2R_b^{\ 3}}{\left(\alpha_i^{\ 2}\right)} \left\{ \frac{2R_b}{\left(\alpha_i^{\ 2} + 4R_b^{\ 2}\right)^2} + \frac{3}{2\alpha_i^{\ 2}} \left[\frac{2R_b}{\alpha_i^{\ 2} + 4R_b^{\ 2}} + \frac{1}{\alpha_i} \arctan\left(\frac{2R_b}{\alpha_i} \right) \right] \right\}$$

$$F_2 = \frac{-\Delta P}{n_r} - \frac{6\mu_{eff} u}{R_{eq}} x_i \left(\frac{R_b}{2} \right) \left[\frac{1}{\left(H + \frac{x_i^{\ 2}}{2R_{eq}} + 1 \right)^2} - \frac{1}{\left(H + \frac{x_i^{\ 2}}{2R_{eq}} \right)^2} \right] ,$$

$$F_3 = \frac{6\mu_{eff} \cdot u \cdot x_i}{R_{eq}} \cdot \left(\frac{-R_b}{2} \right) \cdot \frac{1}{\left(H + \frac{x_i^{\ 2}}{2R_{eq}} + \frac{y_i^{\ 2}}{2R_b} \right)^2} \ ,$$

$$F_4 = \frac{2R_b^{\ 3}}{\left(\alpha_i^{\ 2}\right)} \left\{ \frac{2R_b}{\left(\alpha_i^{\ 2} + y_i^{\ 2}\right)^2} + \frac{3}{2\alpha_i^{\ 2}} \left[\frac{2R_b}{\alpha_i^{\ 2} + y_i^{\ 2}} + \frac{1}{\alpha_i} \arctan\left(\frac{y_i}{\alpha_i} \right) \right] \right\} \ ,$$

$$F_5 = P_u - \frac{\Delta P}{n_r} \cdot (i-1) - \frac{6\mu_{eff} u}{R_{eq}} x_i \left[\frac{-R_b}{2} \cdot \frac{1}{\left(H + \frac{x_i^{\ 2}}{2R_{eq}} \right)^2} \right] \ ,$$

$$\alpha_i^{\ 2} = 2R_b \cdot \left(H + \frac{x_i^{\ 2}}{2R_{eq}} \right).$$

Equation (2) is a function of ΔP, μ_{eff}, BH, R_b, R_{eq}, n_r, u and H. ΔP is a design parameter and known. BH, R_b, R_{eq}, n_r are brush seal properties and they are also known. μ_{eff} can be calculated by using temperature analysis of

Duran et. al. [1]. Only u and H is unknown in Equation (2), and relation between them can be found by using this equation, without requiring any experimental data.

Results and Comparison with Experimental Lift Clearance

Comparison of theoretical hydrodynamic lift clearance found by introducing a MATLAB code for Equation (2) and experimental hydrodynamic lift clearance data is given in Figures 2 and 3. As it can be seen from the figures, the lift clearance data gives highly consistent results with experimental lift clearance data. High speed-stabilization in theoretic lift clearance is the result of including shear heating effect by means of effective viscosity.

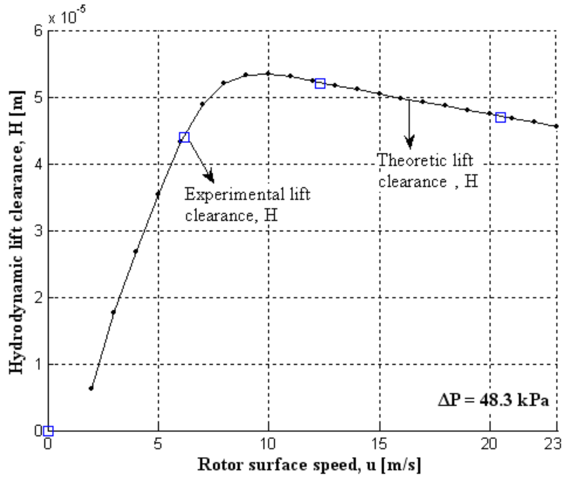

Figure 2 Comparison of theoretic hydrodynamic lift clearance with experimental lift clearance data, ΔP = 48.3 kPa

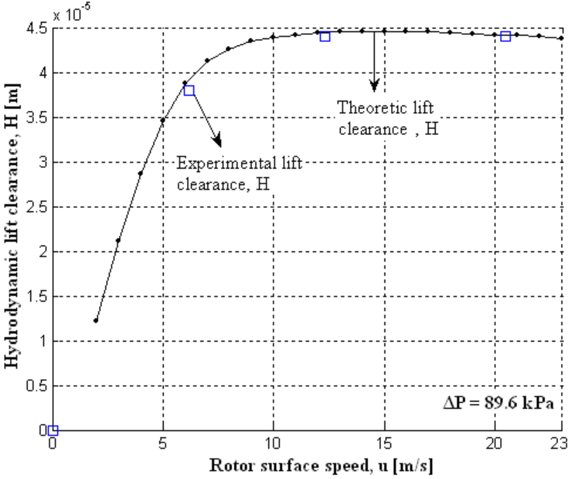

Figure 3 Comparison of theoretic hydrodynamic lift clearance with experimental lift clearance data, ΔP = 89.6 kPa

Theoretic lift clearance change with rotor surface speeds are given in Figure 4 for different pressure loads. As it can be observed form the figure, lift clearance decreases as pressure load increases, which is also the case for real life applications. Oil flow at y-direction increases as pressure load increases, which results in more shear in the oil. As a result of increasing shear mechanisms, dissipated heat is higher for large pressure loads. Therefore, effective viscosity takes smaller values for same rotor speeds at higher pressure loads, which degrades the lift ability of the oil.

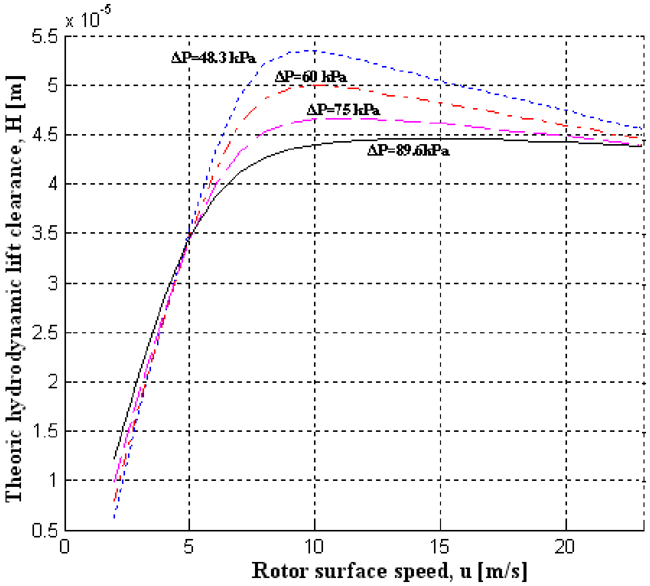

Figure 4 Theoretic hydrodynamic lift clearance change with rotor surface speed for different pressure loads

References

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