LUBRICATION CHARACTERISTICS OF SPIRAL GROOVE LIQUID SEALS FOR USE IN THE CARRIER OF A VANE-TYPE EXTERNAL LPG FUEL PUMP

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ABSTRACT—We analyzed the lubrication characteristics of a design-selected spiral groove liquid seal for the critical component, the carrier, of a rotary vane-type fuel pump developed for external installation on fuel tanks for liquid phase LPG (liquefied petroleum gas) injection (LPLi) vehicles, with the aim of fundamentally improving lubrication performance and so protecting the carrier from early frictional wear damage at its suction face. The main reason for selecting a spiral groove pattern was because the viscosity of liquid LPG is very low, comparable to that of air, and current commercial dry gas seals adopting spiral grooves have been successfully employed in completely noncontacting applications. Utilizing the Galerkin finite element lubrication analysis method, a detailed lubrication characteristic analysis of the seal was performed, and lubrication performance optimization was performed by systematic parameter analyses of the design variables. Compared to the initial reference design, the final optimized spiral groove seal design had a groove depth increased by 66.7% and an equilibrium seal clearance increased by 65.3%. Our model also predicted that under a condition of equilibrium between the closing force of the pumping pressure and the seal opening force, the optimally designed carrier spiral groove liquid seal was capable of maintaining a stable lubricating film with sufficient axial stiffness and thereby demonstrated successful noncontact operation; in addition, leakage through the seal was minimal.

KEY WORDS : External liquefied petroleum gas (LPG) fuel pump, Liquid phase LPG injection (LPLi), Spiral groove, Carrier, Liquid seal

NOMENCLATURE

A' : area [m²]
A : dimensionless area, A'/α
C : centerline land or ridge seal clearance [m]
Cg : groove depth [m]
dc : axial damping [N·m/s]
D : dimensionless axial damping, (Cs/PrR0R0)\(\gamma\)
dg : angular damping [N·ms/rad]
Dg* : dimensionless angular damping, (Cs/PrR0R0)\(\gamma\)\(g\)*
F : opening force [N]
F* : dimensionless opening force, (1/PrR0)\(\gamma\)\(F\)
\(h\) : film thickness [m]
\(h_F\) : groove taper height [m]
\(h_1/h_2\) : film thickness ratio at groove region, 1+Cs/C
\(H\) : dimensionless film thickness, \(h/C - 1 + \gamma R_0(\sin\theta)\beta (R-R_0)\)
\(H_6\) : dimensionless equilibrium film thickness, 1+\(\gamma_0\)\(\gamma R_0(\sin\theta)\beta (R-R_0)\)
\(k_x\) : axial stiffness [N/m]
\(K_{\gamma}\) : dimensionless axial stiffness, \((Cs/PrR0)\gamma\)\(k_x\)
\(\gamma\) : angular stiffness [N·m/rad]
\(K_{\gamma g}\) : dimensionless angular stiffness, \((Cs/PrR0)\gamma\)\(g\)*
\(M\) : restoring moment [N·m]
\(M^*\) : dimensionless restoring moment, \((M/PrR0^2)\gamma\)\(M\)
\(N_g\) : number of groove
\(p\) : pressure [Pa]
\(P\) : dimensionless pressure, \(p/Pr\)
\(Q\) : radial leakage [m³/s]
\(Q^*\) : dimensionless radial leakage, \((12\mu/C^2)\gamma\)\(Q\)
\(r\) : coordinate
\(R\) : dimensionless radius, \(r/r_0\)
\(\theta\) : time [s]
\(W\) : heat generation [W]
\(W^*\) : dimensionless heat generated, \((C/\mu\theta R_0^2)\gamma\)\(W\)
\(W_0\) : groove width
\(W_r\) : ridge width
\(z\) : z-coordinate or axial perturbed displacement of \(h\)
\(Z\) : dimensionless axial perturbed displacement, \(z/C\)
\(\alpha\) : spiral angle [rad]
\(\beta\) : seal coning [rad], \((h_0-h)/(\alpha-\alpha_0)\)

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\[ \beta : \text{dimensionless coning}, \beta^2 r_o/C \]
\[ \gamma : \text{relative misalignment between seal faces}, [\text{rad}] \]
\[ \gamma : \text{dimensionless misalignment or perturbed misalignment}, \gamma r_o/C \]
\[ \gamma_0 : \text{dimensionless equilibrium misalignment} \]
\[ \Gamma : 2A \]
\[ \theta : \theta \text{-coordinate} \]
\[ A : \text{seal operation parameter}, 6\mu_0 r_i^2/p_o C^2 \]
\[ \mu : \text{fluid viscosity} \ [\text{Pa} \cdot \text{s}] \]
\[ \tau : \text{dimensionless time}, \omega t \]
\[ \omega : \text{rotating speed} \ [	ext{rad/s}] \]

**SUBSCRIPTS**

\[ g : \text{groove radius} \]
\[ i : \text{inner radius} \]
\[ o : \text{outer radius} \]
\[ O : \text{equilibrium state} \]

1. **INTRODUCTION**

Interest in the use of alternative fuels is growing rapidly in both the governmental and civilian sectors worldwide. To meet motor vehicle emission regulations, which are globally becoming stricter, and to use natural resources effectively, the use of clean gas fuels in motor vehicle engines has been increasing, promising higher efficiency and lower emissions. LPG (liquefied petroleum gas) is a representative clean gas fuel. In 2009, Korea was the leading nation in the use of LPG vehicles, with over 2.35 million LPG vehicles in service.

The first LPG vehicles adopted fuel supply systems using 2nd generation mixers of the vaporizer type and had problems with inaccurate mixture A/F ratio, slow engine response, low power output, and especially poor cold starting in winter. To solve these problems fundamentally, current LPG vehicles have adopted 3rd generation liquid-phase LPG injection (LPLi) fuel supply systems; as a result, the power output and cold starting performance of LPG vehicles have been improved to be comparable to those of gasoline vehicles.

The most important component module in the LPLi fuel supply system is the fuel pump. Diaphragm-type and centrifugal-type pumps, which are installed inside of fuel tanks, are currently mass produced. In 2003, Korea accomplished a commercialization of exclusively LPLi-engine vehicles for the first time, but the fuel pumps still rely on foreign technologies. To date, many studies have been completed or are currently in progress toward the goal of domestic production of LPLi fuel pumps; however, ensuring the trouble-free, durable operating capability of such pumps, the most important quality for vehicle applications, remains the greatest obstacle.

One of the key problems in LPLi fuel pumps related to durable operating capability is the early tribological failure of bearings and parts in frictional operations, occurring due to the very low viscosity of liquid LPG when used as a lubricant. At an ambient temperature of 20°C, liquid LPG has a viscosity of 1.448×10^-4 Pa·s, lower than that of air, at 1.821×10^-6 Pa·s. Therefore, especially considering that light turbine oil (ISO VG32) at 40°C has a viscosity of 2.615×10^-6 Pa·s, the conditions in an LPG pump create very poor lubrication.

Figure 1 shows a schematic of an LPLi rotary vane-type external fuel pump presently being developed for LPG vehicle applications. As the eccentrically positioned carrier rotor rotates, liquid LPG is pumped from the suction side to the discharge side by the rollers reciprocating within the carrier; simultaneously, the carrier, which freely floats axially, is pressed closely against the suction plate by pressure acting on the discharge plate side. As the viscosity of LPG is very low as mentioned, a relatively large power loss occurs due to frictional rotation of the carrier and, more seriously, an early malfunction of the pump may result from rapid wear at the contact areas. This can be a fatal weakness, as a fuel pump should have an operational lifetime of at least 2-30,000 km. Therefore, a design or method must be introduced to fundamentally improve the lubrication conditions between the carrier and the suction plate despite LPG's poor lubricating performance.

Noncontacting mechanical face seals, using gases as lubricants, are often called dry gas seals and normally have spiral grooves on their sealing faces. Dry gas seals show great potential as precise leakage control devices for turbo and fluid machines operating in severe and contaminated environments, and their application areas have been expanded greatly (Gabriel, 1979; Sedy, 1980; Morrissey, 1996; Cai and Shiomi, 2002). Shapiro et al. (1984) reported that a spiral groove gas seal is one of the most important application candidates for LOX (liquid oxygen) turbopumps because of its properties of preventing rubbing contact, which could ignite catastrophic explosions in liquid-oxygen environments, and effectively restricting leakage.

Generally, any gas-lubricated tribo-elements with ordinary sealing faces scarcely generate a sufficient...