Computers & Fluids 57 (2012) 138–150

Contents lists available at SciVerse ScienceDirect

Computers & Fluids

journal homepage: www.elsevier.com/locate/compfluid

Unsteady numerical simulation of an air-operated piston pump for lubricating greases using dynamic meshes

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ARTICLE INFO

Article history:
Received 27 July 2011
Received in revised form 30 November 2011
Accepted 19 December 2011
Available online 29 December 2011

Keywords:
Numerical simulation
Lubricating grease
Air-operated piston pump
CFD
Dynamic mesh
Layering technique
Leakage flow
Fluidity
Non-newtonian pseudoplastic flow
Pump aspiration

ABSTRACT

This paper presents the numerical simulation of an air-operated piston pump for lubricating greases. The model, based on the dynamic mesh technique, describes the unsteady displacement of the piston using a layering algorithm. The pump driven velocity has been modified using a parametric user defined function (UDF) that covers the whole range of operating points for the pump, as a function of the discharged outlet pressure.

The leakage flow across the feeder plate gap has been analyzed in detail, monitoring its evolution in both forward and backward strokes as a function of the pressure in the adjacent chambers. The comparison between the numerical results and the predictions from the theoretical formulations in the literature for non-newtonian fluids in annular ducts has confirmed the accuracy of the simulation and the correct selection of the discretization for small gaps and inner passages. In addition, the analysis of the flow delivered overtime has provided the numerical distribution and mean values expected from the experimental performance curves supplied by the manufacturer.

Finally, the flow conditions in the aspirating region of the pump have been studied in terms of dynamic viscosity and grease fluidity. It has been observed that the fluidity is restricted to those zones presenting large areas of velocity gradients, like the feeder gap and the vicinity of the aspirating inlet, especially close to the solid walls of pump and drum. For the intermediate positions of both advancement and returning stages, when the piston velocity is maximum, the obtained maps reveal that the induced suction reach significant portions of grease within the drum, similar in distance to the pump diameter, and confirms the order of magnitude estimated with an inspectional analysis of the governing equations of grease motion in the aspirating zone.

1. Introduction

For years, greases have been used as lubricating fluids in a number of industrial applications due to their lubricating capacity and lack of fluidity when stayed at rest (null tensor stresses). This makes them particularly suitable to lubricate open cavities without leakage risk. Unfortunately, this lack of fluidity has been always a clear disadvantage for pumping and delivering grease, especially when high pressures are required for a wide range of applications.

The pumps employed for these purposes are robust equipments, designed to handle the extremely high pressures associated to the lubricating operations. The air-operated single piston generates the volumetric displacement in every stroke, which according to the driven velocity of the reciprocating mechanism, delivers the corresponding flow rate. Typically, these lubricating pumps are composed of two adjacent chambers. The first one is a depressurized single chamber that injects the grease into a second chamber during the forward stroke. When the piston pump is moving back, this second chamber, fully isolated and thus without any leakage flow, is progressively collapsed, venting the flow rate at the required operating pressure (grease acting as an incompressible flow according to Pascal's principle). This design, using two consecutive chambers in a row, avoids the presence of leakage flow during the backward stroke, when the pump is really providing the grease flow rate at high-pressure, but it is susceptible from suffering partial cavitation and breaking-off the fluid continuum during the returning.

Regarding the operation of these pumps, manufactured with an accurate length of the external tube for the different types of commercial drums, they are usually mounted over the tap of the grease drums. The low fluidity of the greases, even more conditioned when operated at low temperatures, requires the employment of follower plates, which are even pushed by strong pneumatic cylinders to convey the grease much more. When these elements are not

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doi:10.1016/j.compfluid.2011.12.014

Nomenclature

A	amplitude (mm); area (mm^2)
ASTM	American Society for Testing Materials
BDC	bottom-dead-center
c	feeder diameter (mm)
CFL	Courant number
d	feeder rod diameter (mm)
D	hydraulic piston diameter (mm)
DOF	degrees of freedom
f	frequency (s^{-1})
h	gap (mm)
k	apparent viscosity or consistency index (Pa.s)
l	gap length (mm)
L	piston stroke (mm)
L_x, L_y	characterisitc lengths (mm)
m	Behavior index (–)
$\dot{m}$	delivered flow rate (gr/min)
n	driven velocity (cycle/min)
NLGI	National Lubricating Grease Institute
p, Δp	discharge pressure (bar)
$Q, \bar{Q}$	volumetric flow rate; Mean volumetric flow rate (m^3/s)
S	crossed-area (mm^2)
t, Δt	time, time step (s)
T	period (s)
TDC	top-dead-center
u	characteristic velocity (m/s)
UDF	user defined function
v	velocity (m/s)
V, V_B	volume, pump net displacement (cm^3)
x, Δx	x-coordinate, longitudinal discretization (mm)
y, Δy	y-coordinate, transversal discretization (mm)

Greek symbols

φ	generic variable
μ	dynamic viscosity (Pa s)
γ	velocity gradient (s^{-1})
ρ	density (kg/m^3)
ω	rotational speed (rpm)
κ	internal gap distance (%)
τ	shear stress (Pa)
Γ	diffusion coefficient (m^2/s)

included, it is very common the arising of important problems in the aspirating region during the piston rising, leading to oscillation or pulsating injection of grease, partial vacuum in the drum or severe compacting of solid packages of grease close to the aspiration.

However, this kind of industrial evidences has a difficult characterization because typical grease is a highly-viscous, opaque fluid, with a variable behavior according to the working temperature or the velocity gradient. Moreover, the high-pressures involved in delivering so reduced flow rates are also a major inconvenience for obtaining reliable values of flow rate or velocity in the small gaps of the pump. Complementarily, the rough operational ranges used in these pumps, as well as the environmental or industrial conditions associated to their use, have extremely limited the development of particular methodologies for their analysis. Nevertheless, some new recent methodologies have arisen for the computational study of volumetric pumps that can be successfully applied for this kind of lubricating pumps with reciprocating operation principle (Houzeaux and Codina [1], Vande Voorde et al. [2], Riemslagh et al. [3]). Since positive displacement pumps operate generating and destroying small volumes, these methodologies require remeshing operations to implement the generation and collapse of cells as the piston displaces overtime (Strasser [4], Kumar et al. [5], Hyun et al. [6]).

This paper describes the numerical modeling of an air-operated piston pump by means of a remeshing technique that employs a layering method to implement the reciprocating displacement of the piston pump. According to the pump geometry, it has been considered an axisymmetric model of the inner parts within the pump housing, including the outer zones of the aspirating inlet where the grease fluidity will be analyzed as a function of the operational parameters. In this case, the grease will be modeled as a non-newtonian, pseudoplastic fluid, with both consistency and behavior indexes known, following the Otswald-de Waele expression. In order to validate the model, the numerical results will be compared with the performance curves of the pump, obtained experimentally, paying particular attention to the pump performance when working at free delivery.

In addition, the leakage flow through the gap of the feeder during back-and-forth strokes has been analyzed in detail, comparing the numerical results with the prediction of the theoretical flow rate for non-newtonian fluids in concentric annuli driven by a pressure gradient (Fredickson and Bird [7], Hanks [8]). The different pressure conditions of the pump have been taken into account using different driven velocities for the forward and backward strokes following a sinusoidal law. Hence, the modifications in the aspirating conditions of the pump can be monitored as a function of the cycles per minute imposed. Finally, the unsteady numerical model has allowed the study of the impact of the different piston positions in the internal flow patterns of the grease for every cycle.

2. Grease characteristics. Lubricating pumps and operating cycle

2.1. Greases rheology

Lubricating greases are, in general, highly-structured colloid dispersions of a thickening component; typically, a metallic soap in a lubricating oil. The most common solution is the use of grease acids of metallic soaps such as lithium, calcium, sodium, aluminum or even barium as thickening elements. The thickening gives consistency to the grease, preventing the fluid leakage or the penetration of contaminant particles, with no penalty on the lubricating properties.

The rheological behavior of lubricating greases is not a common research area in the literature. This particular application in the lubricating industry covers exclusively a 3% of all the manufactured lubricating greases worldwide (Delgado et al. [9]). However, a few references can be found in the bibliography concerning the rheological behavior of greases according to their composition, working temperature or mechanical stress. In particular, it can be cited the work by Delgado et al. [9], where the influence of the thickening soap and the viscosity of the base oil over the grease characteristics is addressed. Other works, like those by Sanchez et al. [10] or Delgado et al. [11,12], deal with the rheological response of lubricating greases with variations in the temperature or in the shear stress.

Nowadays, the greases are standardized using the NLGI classification (*National Lubricating Grease Institute*, [13]). This method is a well-extended reference in the industry because it simplifies the grease selection only to its overall consistency under normal