ton, and what kinds should be avoided? What should be the properties of the boundary layer, how should these properties be measured, and how may such a layer be formed and maintained in service? How strong should it be? How thick? How sharp should be the transition from boundary layer to low-viscosity fluid, and how can this be controlled? What are the effects, beneficial or otherwise, of other types of surface-conditioners such as E-P additives, colloidal graphite or molybdenum sulphide, and indium plating? How are all these questions to be answered if the working fluid is not based on petroleum, but on water or on one of the various families of synthetics? What about a gaseous medium? What about excessively high or low temperatures? What about dirt? And finally, is it necessary to answer all of these questions anyway? In many cases the answer to this last question is "No." As already suggested, it may be possible to design and to apply the device, whether it be a ram, a pump, a rotary motor, or a valve, in such a way that metal-to-metal contact is avoided and hydrodynamic lubrication is effective at all times. This design procedure will often be impossible, however, and therefore answers to the questions must be sought from workers in all pertinent fields, whether they be called hydraulic designers, oil chemists, lubrication engineers, metallurgists, or whatnot.

Conclusion

In conclusion, it has been shown that large lateral forces can be exerted on hydraulic pistons by unsymmetrical pressure distribution in the working clearances, even for very small deviations from ideal dimensions. If these forces, or other lateral forces or moments arising from causes outside the piston-cylinder system itself, are large enough to cause rupture of the lubricating boundary layer, excessive friction and damage result. A superficial picture of the physics of the boundary layer has been given, and a number of questions have been asked to which all concerned with this and related fields are requested to contribute answers. If this paper stimulates the finding and publication of a few of these answers, it will have served its purpose.

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Discussion

G. I. Chinn.[12] This paper is concerned specifically with problems arising in connection with the design of servomechanisms. It should be pointed out that this problem of lateral forces, hydraulic lock, if you will, is present also in industrial hydraulic valves, where grinding of precise tapers on the valve spools to eliminate the unbalancing forces would be economically unfeasible.

About 4 years ago the writer was faced with the necessity of supplying solenoid-actuated balanced-spool valves for a 3000-psi application. After being subjected to this pressure for approximately 1 min, these valves could not be actuated because of locking of the spool against the valve body by lateral hydraulic forces. With the solenoids, end caps, and seals removed from the valves, leakage across the spool-end land in the form of an annular sheet of oil was observed at the instant pressure was applied. In a matter of seconds this annulus broke and gradually diminished to a small segment. Disruption of the annulus was accompanied by hydraulic locking of the spool, to an extent that it was impossible to hammer the spool loose as long as pressure was applied and only with difficulty after release of pressure.

This condition was eliminated by the machining of circumferential grooves, 0.010 in. wide on $^1/_{32}$-in. centers, in the entire width of the lands of the spool, whose diameter was $^5/_8$ in. Pressures of 3000 psi were applied for 1 hr without resultant lock. The fluid used was a commercial-grade, inhibited hydraulic oil having a viscosity of 250 SSU at 100 F. Spool clearance was 0.0005 in. Filtration of the oil was accomplished by industrial-type filters.

The same type of grooves were machined in a $1^1/_8$-in-diam spool, again with beneficial results. Experiments on the larger spool revealed a decrease in leakage with the grooved spool as compared with the ungrooved, and this was attributed to the centering effect of the grooves.

[12] Mem. ASME.