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(54) FLOW RESPONSIVE PRESSURE RELIEF VALVE

(71) We, CATERPILLAR TRACTOR Co., a corporation organized and existing under the laws of the State of California, United States of America, of 100 N. E. Adams Street, Peoria, Illinois 61629, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

While spring-loaded poppet-type pressure relief valves are widely used in a variety of hydraulic circuits, they frequently suffer from unstable response and regulation problems. Generally, these poppet relief valves include a spool with a conical head portion, and upon reaching a predetermined opening pressure, the spool moves to admit a cone of fluid through an annular orifice. Since this orifice necessarily increases in size with higher flow rates, the loading spring must be further compressed and complex fluid impingement and flow forces are exerted on

the head of the poppet relief valve which create stability and regulation problems.

In connection with stability problems, it is apparent that a poppet relief valve should rapidly respond to various operating parameters with a minimum of fluctuation. Unfortunately, relatively erratic operation thereof is often observed at certain flow rates. For example, rapid oscillation of these poppet valves between a fully open position and a nearly closed position is sometimes so severe that the resultant flow and pressure fluctuations are frequently audibly evident. At other times, while it cannot be heard, the extremely fast pressure changes are still felt by an associated hydraulic circuit with an accompanying deleterious effect thereon.

Poppet relief valves should also exhibit a relatively flat, controlled pressure versus flow rate characteristic. That is referred to as pressure regulation and is defined as the variation in pressure over the full flow range expressed as a percentage of the pressure at maximum flow, or as follows:

$$\% \text{ Regulation} = \frac{\text{Press at max. flow} - \text{Press at min. flow}}{\text{Press at max. flow}} \times 100$$

Heretofore, 15% regulation was generally considered acceptable. But this undesirably high percentage was actually acceptable only as a compromise, since it was known that with a lower percentage of regulation the likelihood of significant stability problems greatly increases.

Reference is made to U.S. Patent 3,199,532 for a poppet relief valve constructed to overcome at least a portion of the aforementioned problems. It does this by closely controlling the diametrical clearance between an annular collar on the poppet valve head and a surrounding bore, and also by controlling the axial position of the collar with respect to an annular outlet groove to provide an auxiliary, velocity compensating orifice in series with the primary regulating orifice. It is apparent that the precise dimensional

control required during the manufacture of both the valve head and its associated housing is very expensive. Moreover, even with this added complexity, the poppet relief valve of U.S. Patent 3,199,532 is not believed to have both the combination of good stability and a regulation level below 10%. This combination is particularly hard to achieve when these poppet relief valves are used in high pressure hydraulic circuits, for example, above 2000 psi (140 Kg per sq. cm.). Still further, these problems are compounded when they are expected to handle a relatively broad flow range, for example, from zero to 130 gpm (0 to 8.2 litres per sec.).

According to the invention, a poppet-type pressure relief valve comprises a housing having an outlet chamber and an inlet passage opening into the chamber to define an

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annular valve seat therebetween; a spool disposed for axial movement in the housing on the outlet chamber side of the annular seat and having a conical (which in this context includes frusto-conical) nose portion thereon; spring means disposed between the housing and the spool for biasing the spool axially in one direction in which the conical nose portion moves towards the seat to engage the seat and close the valve and whereby the spool is axially movable in the opposite direction to open the valve by fluid pressure in the inlet passage; and the surface of the spool being shaped to provide, downstream of the conical nose portion, a first annular frusto-conical surface portion inclined to the spool axis at a greater angle than the nose portion and, downstream of the first surface portion, a further annular surface portion inclined to the spool axis at a greater angle than the first surface portion; the arrangement being such that upon initial opening of the spool a thin conical fluid stream, in use flowing axially over and parallel to the conical nose portion, glances outwardly primarily off the first surface portion of the spool into the outlet chamber and produces on the spool a reaction a small proportion of which is an axial component, and upon further opening of the spool a thicker fluid stream, in use flowing axially over and parallel to the conical nose portion, significantly impinges on and is deflected outwardly off the further surface portion to the outlet chamber and produces on the spool a reaction a larger proportion of which is an axial component.

This valve may exhibit a relatively flat controlled pressure versus flow rate characteristic, and a rapid, yet stable response through a broad range of fluid flow rates.

One example of a valve constructed in accordance with the invention, and one prior art construction for comparison purposes are illustrated in the accompanying drawings, in which:—

Figure 1 is a schematic diagram of an hydraulic circuit incorporating the valve which is shown in section;

Figure 2 is a fragmentary view of part of the valve shown in an open position corresponding to relieving fluid at a relatively low fluid rate;

Figure 3 is a view similar to Figure 2, the valve being shown in a more widely open position corresponding to relieving fluid at a relatively high flow rate; and,

Figure 4 is a view similar to Figure 2, but of a conventional poppet pressure relief valve.

Figure 1 shows a hydraulic circuit 10 which includes a poppet pressure relief valve 12 in accordance with the present invention. The hydraulic circuit also includes a driven hydraulic pump 14 for communicating fluid

from a reservoir 16 to a selector valve 18 by way of a normally pressurized inlet conduit 20. Upon manually operating the selector valve, fluid is communicated from the inlet conduit to either end of a double acting hydraulic jack 22 through a conduit 24 or a conduit 26, and is relieved from the opposite end of the jack by way of a drain conduit 28 to the reservoir.

The poppet relief valve 12 serves to limit the maximum operating pressure of the hydraulic circuit 10 by being in fluid-relieving communication with the inlet conduit 20 by way of a branch conduit 30, and a cylindrical inlet passage 32 formed in a valve housing 34. The inlet passage has a central longitudinal axis 36 and opens outwardly into an annular outlet chamber 38 in the housing and thus define an annular valve seat 40 therebetween. The outlet chamber is in open communication with the reservoir 16 through an outlet passage 42 and a drain conduit 44. Also, an internal passage 46 is formed in the housing in open communication with the outlet chamber on the opposite side thereof so that fluid therein may return to the reservoir. A valve bore 48 having a diameter slightly larger than the valve seat and a retainer bore 50 are also serially formed in the housing along the axis 36. Further, a pilot poppet valve bore 52 opens on the internal passage 46 and is arranged axially in aligned relation with a cylindrical pocket 54 defined in an externally threaded retaining member 56 which is screw threadably received by the housing 34.

Upon further reference to FIG. 1, it is apparent that a cylindrical retaining cup 58 is sealingly disposed in the retainer bore 50 of the housing 34 in such a manner that its internal chamber 60 defined therein opens on the valve bore 48. A cylindrical through passage 62 and an annular pilot poppet valve seat 64 are also formed centrally in the cup, and a conventional pilot poppet relief valve 66 is associated therewith. The pilot poppet valve has a conical head 68 and a reduced diameter elongated stem 70 extending therefrom, and a relatively stiff or high rate compression spring 72 is seated intermediate the pocket 54 of the retaining member 56 and the pilot poppet head to bias it into closed engagement with the valve seat. Upon reaching a predetermined pressure of, for example, 2300 psi (162 Kg per sq. cm.) in the chamber 60, the pilot poppet relief valve opens to permit fluid flow from the chamber to the internal passage 46.

The flow responsive poppet relief valve 12 includes a poppet spool 74 having a radially outwardly flared head 76 which is generally disposed within the outlet chamber 38, and an elongate cylindrical body 78 which is disposed for sealed axial sliding movement

in the valve bore 48. A cylindrical pocket 80 and a spring-receiving pocket or seat 82 are formed inwardly from the opposite ends of the spool to thereby provide a wall 83 centrally thereof in which is disposed a flow-controlling orifice 84. Also, in a beneficial manner, an annular groove 86 is disposed around the periphery of the spool and an oblique passage 88 normally communicates pressurized fluid from the inlet passage 32 to the annular groove via the pocket 80 in order to hydraulically balance and centre the spool for improved response.

The poppet spool 74 is biased rightwardly as viewed in FIG. 1 by a light rate compression spring 89 which is disposed in the pocket 82 and seated against the retaining cup 58. Thus, the outwardly flared head 76 of the spool is urged into closed engagement with the annular valve seat 40 in axially facing relation to the inlet passage 32. As best shown in FIG. 2, the outwardly flared head includes in serially arranged order a frusto-conical nose portion 90, a cylindrical step 92, and an outwardly flared, fluid diverting surface portion 93. More particularly, the fluid diverting surface portion 93 includes a gradually sloping leading portion or frusto-conical surface 94, and an annular flange 96 providing a more steeply sloping shoulder portion or annular surface 98 about its periphery which is disposed in a plane substantially at a right angle to the axis 36. It is apparent from the illustration that the frusto-conical nose portion 90 has a cone angle of approximately 60° and the frusto-conical surface 94 formed downstream thereof has a cone angle of approximately 90°, so that with initial opening of the poppet relief valve 12, a thin conical stream of fluid is relieved leftwardly when viewing FIG. 2 from the inlet passage into the outlet passage 38 and directed impingingly against the frustoconical surface 94 at a low angle of incidence. Thus, the operating condition of FIG. 2 corresponds to relieving fluid at a low flow rate, and the low angle of incidence or impingement of the fluid on the outwardly flared surface portion 93, and particularly, the frustoconical surface 94, is such as to cause a low axial force serving to lift the outwardly flared head 76 away from the valve seat 40.

However, further leftward opening movement of the flow responsive poppet relief valve 12 corresponding to the position shown in FIG. 3 permits a thicker conical stream of fluid to be relieved outwardly to the chamber 38. Subsequently at least a portion of the thicker stream impinges on the outwardly flared surface portion 93 at an effectively greater angle of incidence. This greater angle of incidence of the fluid adjacent the intersection of the frustoconical surface 94 and annular surface 98 provides a

predetermined greater amount of lift, or leftward axial force tending to open the poppet relief valve and hence greater magnification of the flow forces acting on the outwardly flared head 76.

In this manner the flared surface portion 93 of the poppet relief valve 12 is profiled for facing exposure to a thin conical fluid stream at a predetermined axially low force transmitting rate coinciding with the low angle of incidence, and is additionally profiled for axially greater force-transmitting response to a thicker conical fluid stream coinciding with a portion thereof impinging thereon at a greater angle of incidence. Such proportioned lift, in opposition to the force of the compression spring 89, greatly increases the stability of the valve and establishes a more constant flow rate for a given pressure level in the inlet passage 32.

While the operation is believed clearly apparent from the foregoing description, further amplification will subsequently be made in a brief summary of such operation. With reference to FIG. 1, and assuming that the hydraulic pump 14 is started to direct fluid at gradually increasing pressure to the inlet conduit 20, the branch conduit 30 and the inlet passage 32, fluid passes through the flow-controlling orifice 84 in the closed poppet relief spool 74 and pressure rises in the spring chamber 60. When the pressure in the chamber reaches the predetermined opening pressure of approximately 2300 psi (162 Kg per sq. cm.), the pilot poppet valve 66 opens or moves to the left, when viewing FIG. 1, away from its seat 64, in opposition to the loading of the spring 72. Fluid is then relieved from the spring chamber to the relief passage 46 at the rate of fluid flow through the flow-controlling orifice 84. Upon establishing a relatively low but predetermined pressure drop across the orifice, the chamber pressure is lowered sufficiently with respect to the pressure in the inlet passage 32 that the main poppet relief spool 74 opens to relieve fluid relatively directly from the inlet passage to the outlet chamber 38 and back to the reservoir 16. Thus, the main poppet relief spool opens at a pressure slightly above that required to open the pilot poppet valve.

It will be appreciated that the poppet relief valve 12 is substantially immediately responsive to the pressure changes in the inlet passage 32 because of the small mass of the main poppet spool 74, its low rate spring 89, and the intercooperation between the flow-controlling orifice 84 in the poppet spool and the pilot poppet valve 66. Further, the outwardly flared head portion 76 of the main poppet spool includes two surfaces 94 and 98 thereon that are individually disposed in a predetermined angular facing relation with respect to the stream of

fluid impinging thereon to gain minimal force assisting the lift, or leftward movement opening away from the annular valve seat 40, when relieving fluid at a low flow rate, and yet to gain additional force assisting the lift when operating at a high flow rate.

This predetermined proportionate gain capability of the outwardly flared head 76 of the main poppet spool 74 is better appreciated with reference to FIGS. 2 and 3. In FIG. 2, the spool is initially opened a distance D_1 , to permit a thin conical fluid stream of thickness T_1 to impinge on the outwardly flared surface portion 93 as indicated by the arrow identified by the letter A. As illustrated, this thin stream beneficially impinges substantially centrally upon the frusto-conical surface 94 at a low angle of incidence of approximately 150° due to the flow directing cooperative relationship of the frusto-conical nose portion 90 and the cylindrical step 92. Preferably, this surface 93 is only gradually inclined or flared outwardly at an angle of incidence within the range of from 10° to 20° with respect to the nose portion. Thereafter, this thin stream makes minimal contact with the annular flange 96 at the shoulder 98 because it is primarily deflected obliquely outwardly thereof as indicated by the arrow identified by the letter B. This greatly enhances the stability of the poppet relief valve 12 at low flow rates.

As shown in FIG. 3, however, when the poppet spool 74 is opened to a greater axial distance D_2 between the frusto-conical nose portion 90 and the valve seat 40, a thicker conical fluid stream of thickness T_2 is permitted to impinge on the outwardly flared surface portion 93. But, as illustrated by the arrow identified by the letter C, at least the radially outermost portion of the stream impinges further outwardly on the flared surface portion adjacent the intersection of the frustoconical surface 94 and annular surface 98. Thus, a portion of the thicker conical fluid stream impinges substantially directly on the annular surface 98 over a greater surface area and at an angle of incidence of approximately 60° , as illustrated, or preferably within the range of approximately 50° to 70° when the poppet spool is relieving at a high flow rate. This results in a significantly magnified axial force tending to open the spool, or greater valve lift and, hence, improved overall regulation of the relief valve.

The illustrated valve exhibits a rapid rate of response while also being stable in its flow controlling functions. In addition, it exhibits a relatively flat, controlled pressure versus flow rate characteristic with an observed regulation of approximately 8%.

The aforementioned operation is in marked contrast to the uncontrolled response of a

conventional poppet relief valve as shown in the fragment of FIG. 4, for example. It is clearly apparent that even with a low rate of fluid flow, the stream impinges at an abrupt angle of incidence of approximately 60° upon the shoulder of the valve head as illustrated by the arrow identified by the letter E. Thereafter, further opening of the prior art valve generally retains the same angle of incidence. Consequently, the valve is unstable, particularly at low flow rates, and tends to oscillate in an undesirable manner as set forth above in the introduction hereto.

In view of the foregoing, it is readily apparent that the poppet relief valve 12 according to the present invention is responsive to flow thereon in a compensating manner to provide a stable response and a high degree of pressure regulation, which combination has been heretofore elusive. The valve is also economical in its construction, and is adaptable for use in both high pressure and broad flow range hydraulic circuits.

It is to be further appreciated that the poppet relief valve 12 according to the present invention need not be utilized with the pilot poppet valve 66, but rather can be directly opened by exposure to a predetermined pressure within the inlet passage 32 in opposition to the biased loading of solely the compression spring 89, since the chamber 60 could then be arranged in open communication with the reservoir 16.

WHAT WE CLAIM IS:—

1. A poppet-type pressure relief valve comprising a housing having an outlet chamber and an inlet passage opening into the chamber to define an annular valve seat therebetween; a spool disposed for axial movement in the housing on the outlet chamber side of the annular seat and having a conical (which in this context includes frusto-conical) nose portion thereon; spring means disposed between the housing and the spool for biasing the spool axially in one direction in which the conical nose portion moves towards the seat to engage the seat and close the valve and whereby the spool is axially movable in the opposite direction to open the valve by fluid pressure in the inlet passage; and the surface of the spool being shaped to provide, downstream of the conical nose portion, a first annular frusto-conical surface portion inclined to the spool axis at a greater angle than the nose portion and, downstream of the first surface portion, a further annular surface portion inclined to the spool axis at a greater angle than the first surface portion; the arrangement being such that upon initial opening of the spool a thin conical fluid stream, in use flowing axially over and parallel to the conical nose portion, glances outwardly primarily off the

fluid impinging thereon to gain minimal force assisting the lift, or leftward movement opening away from the annular valve seat 40, when relieving fluid at a low flow rate, and yet to gain additional force assisting the lift when operating at a high flow rate.

This predetermined proportionate gain capability of the outwardly flared head 76 of the main poppet spool 74 is better appreciated with reference to FIGS. 2 and 3. In FIG. 2, the spool is initially opened a distance D_1 to permit a thin conical fluid stream of thickness T_1 to impinge on the outwardly flared surface portion 93 as indicated by the arrow identified by the letter A. As illustrated, this thin stream beneficially impinges substantially centrally upon the frustoconical surface 94 at a low angle of incidence of approximately 150° due to the flow directing cooperative relationship of the frusto-conical nose portion 90 and the cylindrical step 92. Preferably, this surface 93 is only gradually inclined or flared outwardly at an angle of incidence within the range of from 10° to 20° with respect to the nose portion. Thereafter, this thin stream makes minimal contact with the annular flange 96 at the shoulder 98 because it is primarily deflected obliquely outwardly thereof as indicated by the arrow identified by the letter B. This greatly enhances the stability of the poppet relief valve 12 at low flow rates.

As shown in FIG. 3, however, when the poppet spool 74 is opened to a greater axial distance D_2 between the frusto-conical nose portion 90 and the valve seat 40, a thicker conical fluid stream of thickness T_2 is permitted to impinge on the outwardly flared surface portion 93. But, as illustrated by the arrow identified by the letter C, at least the radially outermost portion of the stream impinges further outwardly on the flared surface portion adjacent the intersection of the frustoconical surface 94 and annular surface 98. Thus, a portion of the thicker conical fluid stream impinges substantially directly on the annular surface 98 over a greater surface area and at an angle of incidence of approximately 60° , as illustrated, or preferably within the range of approximately 50° to 70° when the poppet spool is relieving at a high flow rate. This results in a significantly magnified axial force tending to open the spool, or greater valve lift and, hence, improved overall regulation of the relief valve.

The illustrated valve exhibits a rapid rate of response while also being stable in its flow controlling functions. In addition, it exhibits a relatively flat, controlled pressure versus flow rate characteristic with an observed regulation of approximately 8%.

The aforementioned operation is in marked contrast to the uncontrolled response of a

conventional poppet relief valve as shown in the fragment of FIG. 4, for example. It is clearly apparent that even with a low rate of fluid flow, the stream impinges at an abrupt angle of incidence of approximately 60° upon the shoulder of the valve head as illustrated by the arrow identified by the letter E. Thereafter, further opening of the prior art valve generally retains the same angle of incidence. Consequently, the valve is unstable, particularly at low flow rates, and tends to oscillate in an undesirable manner as set forth above in the introduction hereto.

In view of the foregoing, it is readily apparent that the poppet relief valve 12 according to the present invention is responsive to flow thereon in a compensating manner to provide a stable response and a high degree of pressure regulation, which combination has been heretofore elusive. The valve is also economical in its construction, and is adaptable for use in both high pressure and broad flow range hydraulic circuits.

It is to be further appreciated that the poppet relief valve 12 according to the present invention need not be utilized with the pilot poppet valve 66, but rather can be directly opened by exposure to a predetermined pressure within the inlet passage 32 in opposition to the biased loading of solely the compression spring 89, since the chamber 60 could then be arranged in open communication with the reservoir 16.

WHAT WE CLAIM IS:—

1. A poppet-type pressure relief valve comprising a housing having an outlet chamber and an inlet passage opening into the chamber to define an annular valve seat therebetween; a spool disposed for axial movement in the housing on the outlet chamber side of the annular seat and having a conical (which in this context includes frusto-conical) nose portion thereon; spring means disposed between the housing and the spool for biasing the spool axially in one direction in which the conical nose portion moves towards the seat to engage the seat and close the valve and whereby the spool is axially movable in the opposite direction to open the valve by fluid pressure in the inlet passage; and the surface of the spool being shaped to provide, downstream of the conical nose portion, a first annular frusto-conical surface portion inclined to the spool axis at a greater angle than the nose portion and, downstream of the first surface portion, a further annular surface portion inclined to the spool axis at a greater angle than the first surface portion; the arrangement being such that upon initial opening of the spool a thin conical fluid stream, in use flowing axially over and parallel to the conical nose portion, glances outwardly primarily off the



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- first surface portion of the spool into the outlet chamber and produces on the spool a reaction a small proportion of which is an axial component, and upon further opening of the spool a thicker fluid stream, in use flowing axially over and parallel to the conical nose portion, significantly impinges on and is deflected outwardly off the further surface portion to the outlet chamber and produces on the spool a reaction a larger proportion of which is an axial component.
2. A valve according to claim 1 wherein the housing has a bore coaxial with the inlet passage and annular valve seat and to the side of the outlet chamber remote from the inlet passage, the spool being reciprocable in the bore.
3. A valve according to claim 1 or claim 2, in which the conical fluid stream glances, in use, against the first surface portion at an angle of incidence between 10° and 20° .
4. A valve according to any one of the preceding claims, in which the conical fluid stream impinges, in use, against the further surface portion at an angle of incidence of between 50° and 70° .
5. A valve according to any one of the preceding claims, in which the frusto-conical first surface has a cone angle of substantially 90° .
6. A valve according to any one of the preceding claims, in which the spool has a cylindrical step portion interconnecting the conical nose portion and the frusto-conical first surface portion.
7. A valve according to any one of the preceding claims, in which the further surface portion is an annular shoulder inclined at substantially 90° to the spool axis.
8. A valve according to any one of the preceding claims, in which the conical nose portion has a cone angle of substantially 60° .
9. A valve according to claim 1, substantially as described with reference to Figures 1, 2 and 3 of the accompanying drawings.

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