A STUDY OF THE IMPULSE VALVE
FOR UGANDA HYDRAULIC RAM PUMP

BY

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Background

E. Schiller and P. Kahangire carried out an experimental (1) and an analytical study (2) of the automatic hydraulic ram pump. In the analytical study, the impulse valve was assumed to close instantaneously. This restrictive assumption was necessitated by the lack of knowledge of the dynamic behaviour of the impulse valve at the time. The present study seeks to develop a mathematical model for predicting the dynamic behaviour of the impulse valve as it closes. Such a model will lead us to a better understanding of how the shape of the impulse valve affect the performance of the hydraulic ram. This will enable us to improve the design of the impulse valve for optimum performance of the hydraulic ram.
The Mathematical Model

The accompanying paper (3) describes a mathematical model for an impulse valve with a weighted valve flap. In the mathematical model, the one-dimensional fluid flow equations of the hydram cycle are solved by a numerical finite difference method. The finite difference method is chosen because quite complex physical models can be incorporated into the solution procedure via the finite difference formulation. The computer program contains about 550 lines of FORTRAN statements and it takes about 2.5 minutes to compute a complete hydram cycle (2500 iterations) on an IBM-XT compatible.

Fig. 1: Schematic diagram of the impulse valve

In the present study, the valve arrangement is different. The valve flap is a rubber disc with a central location hole. The central hole fits into a vertical sleeve which positions it to close upwards onto a perforated (the orifice) conical valve seat (see Fig. 1). As the water flows upwards past the outer edges of the valve flap and into the orifice, a pressure difference is generated between the bottom and top surfaces of the valve flap. As the pressure on the bottom surface is higher, the outer edge of the valve flap is push upwards. If the flow is fast enough, the valve flap closes itself on to the conical valve seat and stops the flow. The mathematical model as described in reference 3 still applies except that there is no period 2. In period 3, the movement of the outer edge of the valve flap is computed from an algebraic expression which gives the relationship between the deflection of the outer edge and the pressure difference between the top and bottom surfaces of the valve flap.
Experimental Investigation

A parallel experimental investigation was carried out to obtain data to test the numerical computational prediction procedure. Experiments were run for different rubber hardness as well as different thickness.

Physical Models

Deflection of Rubber Flap

The rubber valve flap is assumed to deflect under a uniform pressure loading $p$. The deflection of the outer edge of the rubber flap is given by:

$$
Y_{\text{max}} = \frac{3 \rho a^4 (1-\nu^2)}{16 E h^3} \left[ \frac{4 (1-s^2)(3+\nu)}{(1+\nu)} + \frac{16 s^2 (1+\nu)(\ln(1/s))^2}{(1-\nu)(1-s^2)} \right]
$$

$$
- \frac{4 s^2 (3+\nu) \ln(1/s)}{(1-\nu)} - \frac{(1-s^4)(5+\nu)}{(1+\nu)}
$$

where

- $Y_{\text{max}}$ is the deflection at the outer edge
- $a$ is the outer radius of rubber disc
- $b$ is the inner radius of rubber disc
- $s$ is the ratio $(b/a)$
- $\nu$ is the Poisson's ratio of rubber

The effective pressure exerting on the rubber disc is computed from the expression

$$
p = 0.5 \rho V_a^2 (C_d + C_a) + 0.5 V_r^2 C_r
$$

where

- $V_a$ is the velocity at the tip of the valve flap
- $V_r$ is the radial velocity between the valve flap and valve seat
- $C_d$, $C_a$, $C_r$ are pressure loss coefficients
The Computer Program

A listing of the computer program is attached. An explanation of the meaning of the variables are given at the beginning of the program.

Results and Discussion

Although the present prediction procedure employs a simple quasi-steady model for the closure of the impulse valve flap, it is possible to procure agreement with the experimental results of the rate of closure of the valve flap (see Fig. 2 to 7) by suitable adjustment of the pressure coefficient $C$.

The theoretical predictions of global performance data (such as volumetric flow rates through the impulse and delivery valves, and the number of beats per minute) are compared with the experimental results in Tables 1 and 2. The trend shown by the experimental results are well predicted by the present model. However, the predicted water flowrates through both the impulse and delivery valves fall at a slower rate than the experimental values.

References


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Fig. 2a & 2b: Variation of Pressure & Impulse Valve Displacement During Closure.

\( F = 540,000 \text{ N/m} \)
\( t_v = 0.0127 \text{ m} \)
\( P_d = 0.12 \text{ N/m}^2 \)
FIG. 3a & 3b: VARIATION OF PRESSURE & IMPULSE VALUE DISPLACEMENT DURING CLOSURE

\[ E = 540,000 \text{ N/m} \]
\[ t_v = 0.0127 \text{ m} \]
\[ p_d = 0.2 \times 10^6 \text{ N/m}^2 \]
Fig. 46 & 4b

![Variation of Valve Displacement & Pressure During Valve Closure](image)

$E = 540,000 \text{ N/m}$

$t_v = 0.0127 \text{ m}$

$p_a = (37 \text{ psi}) \times 0.25 \times 10^6 \text{ N/m}^2$
FIG. 5a & 5b: VARIATION OF PRESSURE & IMPULSE VALVE DISPLACEMENT DURING CLOSURE

E = 540,000 N/m

\( t_r = 0.0127 \) m

\( P_d = 0.35 \times 10^6 \) N/m²
FIG. 66: VARIATION OF PRESSURE & IMPULSE VALUE
DISPLACEMENT DURING CLOSURE

\[ E = 540,000 \text{ N/m} \]
\[ l_v = 0.00953 \text{ m} \]
\[ p_d = 0.12 \text{ N/m}^2 \]
Fig. 7a & 7b: Variation of Pressure & Impulse Valve Displacement during Closure

\[ E = 540,000 \text{ N/m} \]
\[ t_v = 0.00635 \text{ m} \]
\[ P_d = 0.143 \times 10^6 \text{ N/m}^2 \]
PROGRAM FOR PREDICTING THE PERFORMANCE OF A HYDRAULIC RAM PUMP

VERSION 2.0 (26TH MAY 1988) (FORTRAN-77)

WASTE VALVE TYPE: RUBBER DISC FLAP CLOSING UPWARDS ONTO CONICAL MULTI-HOLE VALVE SEAT

For theoretical background, please refer to:- 
'A study of the dynamic characteristics of the impulse valve of the hydram' by S.Y. Goh

Put ncycle=2 to compute over 2 cycles
nwrite=0 if you do not want a printout of ti,yi,vi etc.
-------- drive pipe --------
h is the water drive head
dp is the internal diameter of drive pipe
al is the length of drive pipe
tp is the wall thickness of drive pipe
-------- impulse valve --------
a is the external radius of rubber valve flap
b is the internal radius of rubber valve flap
tv is the thickness of the rubber valve flap
er is the Modulus of Elasticity of the rubber
poisr is the Poisson's ratio of the rubber
cdamp is the damping coefficient of valve flap vibration
wn is the frequency of valve flap vibration
freq is factor in frequency formula for valve flap vibration
dor is the effective (single hole) orifice diameter
do is the actual hole diameter of each single hole
alo is the length of the orifice holes
de is the impulse valve chamber diameter
gapmax is the maximum reference gap at outer edge
ymax is the gap when flap is undistorted (flat)
-------- delivery valve --------
ddv is the effective (single hole) delivery valve diameter
-------- properties --------
den is the density of water
vis is the viscosity of water
ew is the Bulk Modulus of water
es is the Modulus of Elasticity of steel
pois is the Poisson's ratio for steel
-------- output --------
qwlpm is the flowrate through the impulse valve (litres per min)
qtlpm is the flowrate through the delivery valve(litres per min)
beat is the number of beats (cycles) per minute

The results will be stored in a file 'RESULT'.
This file can be printed out or examined through an editing program.

common/gen/ctp,cte,ctda,ctr,ap,arp0,arop,vp,vpiml
1 ,voi,vpmax,qwaste,pr,dt,pstat
common/dimen/h,dp,tp,al,alo,do,dor,de,ddv
common/prop/den,vis,ew,es,pois
common/press/pa,papsi,pdgpsi
common/coeef/cp,cdv,cd,ca,cri,cr2,co
common/flap/a,b,td,er,poisr,cdamp,freq
common/osc/vmass, wn, cdampt

open(3, file='result')

! iteration control parameters 
! data ncycle, nmax, nitn, nwrite/2, 10000, 10, 1/

! specify time step for each period
! data dt1, dt2, dt3, dt44, dt4, dt5, dt6/
! 1 .001, .0005, .0005, .0005, .0005, .0005, .0005/

! specify timestep for printout
! data dtpr0, dtpr1, dtpr2, dtpr3, dtpr4, dtpr5, dtpr6/
! 1 .001, .001, .001, .001, .001, .001, .001/

! rubber flap dimensions and constants
a=.054
b=.0151
tv=.00635
er=5400000.
cdam=2.6
freq=4.35
ro=a-b
dv=2.*a
dvi=2.*b

! dimensions of hydram
h=1.89
dp=0.053
tp=.0032
al=9.85
alram=.40
alo=.0125
do=.0045
dor=.0517
des=.8*.0254
ddv=.0311
ymax=.0096
gapmax=.012

! property constants and pressure
den=1000.
vis=.00116
pi=3.1416
ew=2.17e9
es=1.90e11
pois=.3
poisr=.4
ef=1./ew+(5.-4.*pois)*.25*dp/(tp*es)
ef=1./ef
papsi=14.7
pa=101325.

! pdgpsi is the delivery pressure (psig)
pdgpsi=21.
pd=pa*(pdgpsi+papsi)/papsi
pdg=pa-pd
pstat=den*9.81*h

! pressure loss coefficients

! other weighting constants
fadv=.2
  eff=1.
  fydot=.75
  fdt=1.
  pcr=1.
  cr=cr1
cop=co

c  aaaaaaaaaaaaaaaaaaa compute areas and area ratios aaaaaaaaaaaaaaaaaaa
  pid4=.25*pi
  ao=pid4*dor*dor
aa=pid4*(de*de-dv*dv)
av=pid4*(dv*dv-dvi*dvi)
ap=pid4*dp*dp
  ae=pid4*de*de
arm=max*pi*dv
adv=pid4*ddv*ddv
aroa=ao/aa
arorm=ao/arm
arop=ao/ap
arpo=ap/ao
arva=av/aa
aro=ao/ae
ardvp=adv/ap

C  ******** calculate area-corrected pressure coefficients *************
c
te=aroe*aroe*ce
ctp=arop*arop*cp
tda=aroa*aroa*cd
tda=ctd+cta
tcr=arorm*arorm*cr
tc=ctd+cta+cct

c  oooooooooooooooooooooooooo oscillation parameters oooooooooooooooooo
vmass=av*tv*den
det=den*9.81*(a**4-b**4)*(1.-pois**2/pois)
wn=freq*sqrt(er*tv*tv/det)
cdampt=cdamp*0.5*den*av

c  bbbbbbbbbbbbbbbbbbbbbbbbbb start of each cycle bbbbbbbbbbbbbbbbbbbbb
nc=0
cmax=9.81*den*h
tilim=100.
tstart=0.
xi=0.
xi1=0.
yc=0.

t10 vpi=1.0e-20
  vo1=1.0e-20
  vpi4=0.
npe=0
  qiv=0.
  qdv=0.
  qwaste=0.
  vpim1=0.
  vopax=0.
  vpmx=0.
  vpt=0.000001
  yim1=0.
y1=0.
t1=tstart
t2=tstart
t1=tstart
dt=dt1
dtpr=dtpr1
np=1
akti=1.
vol=0.
yv=yi+xi
yvm1=yim1+xim1

start of time step within each cycle

do 730 i=2,nmax
dt0=dt
if(dtpr0.ne.100.)dtpr=dtpr0
ns=dtpr/dt
go to (100,200,300,400,500,600),np

*************** compute velocity in drive pipe ***************

1111111111111111111111111 period one 111111111111111111111111111

100  co=0.
cotda=0.
cotr=0.
timl=ti
ti=ti+dt
vol=vol+ap*vpi*dt
yvol=vol/ae
if(yvol.ge.yc)go to 110
vimpl=vpi
call vpipe
if(vpi.gt.vpmax)vpmax=vpi
call oscil(xi,ximl,dt0,dt,xipl)
iy=xipl
ximl=xi
xi=xipl
if(float(i-2)/float(ns).ne.float((i-2)/ns))go to 105
if(nwrite.eq.1)write(3,30)iti,yi,vpi,pr,qtot,np
105 continue
go to 730
110 write(*,*)'PERIOD ONE PASSED'
np=3
dt=dt3
dtpr=dtpr3
ti=ti
go to 730

2222222222222222222222222 period two 2222222222222222222222222222

200  co=cop
cotr=aroa*aroa*cd
cotr=aroa*aroa*ca
cotr=cotr+cta
cotr=arorm*arorm*cr
timl=ti
ti=ti+dt
if(vpi.ge.vpt)go to 210
vimpl=vpi
call vpipe
if(vpi.gt.vpmax)vpmax=vpi
qwaste=qwaste+ap*vpi*dt
go to 700
210 write(*,*)'PERIOD TWO PASSED'
np=3
dt=dt3
dtpr=dtpr3
t2=ti-t1
go to 730

3333333333333333333333333 period three 333333333333333333333333333
C
300  co=cop
     iydot=0
     tim1=ti
     ti=ti+dt
     if(ti.gt.ti1im)dt=fdt*dt3
     yip0=1.
     vpim1=vpi

C
310  gap=ymax-yi
     if(gap.lt.0.)gap=0.00000001
     if(gap.gt.gapmax)gap=gapmax
     cr=cr1+cr2*(gap/gapmax)**pcr
     ctd=aroa*aroa*cd
     cta=aroa*aroa*ca
     ctda=ctd+cta
     ar=pi*dv*gap

     arvo=av/ao
     aror=ao/ar
     ctr=aror*aror*cr
     ydot=(yi-yim1)/dt

     teta=asin(yi/ro)
     rocos=ro*cos(teta)
     dvol=pi*ro*ro*ydot*(a/rocos+.66667)

     var=aroa*voi-ydot-dvol/aa
     rvadvo=var/voi
     ctda=ctda*rvadvo*rvadvo
     if(var.lt.0.)ctda=-ctda

     vr=aror*voi-dvol/ar
     rvrdvo=vr/voi
     ctr=cr*rvrdvo*rvrdvo
     if(vr.lt.0.)ctr=-ctr

     call vpipe

     ct=ctda+ctr
     p35=.5*den*voi*voi*ct
     if(p35.gt.cmax)p35=cmax

     call ydist(p35,yip1)

     if(yip1.lt.ymax)go to 320
     write( *,* )'PERIOD THREE PASSED'
     yi=ymax
     xi=0.
     xim1=0.
     voi=0.
     vpi=0.
     vomax=0.
     write(3,30)i,ti,yi,vpi,pr,vomax,np
     write(3,48)
     np=4
     tilim=.8*ti
     t3=ti-t2-t1
     sq=0.
     ac=sqrt(ef/den)
     pe=2.*al/ac
     hvpi=0.
     t40=ti
     np44=100
     dt=dt4
dtpr=dtpr4
dpmaxg=vmax*sqrt(den*ef)
\[ p_{\text{max}} = p_{\text{stat}} + d_{\text{pmax}} \]
\[ p_{\text{max}} = p_{\text{max}} + p_a \]
\[ a_{\text{kmax}} = 5 \times \text{denap} \times a_{\text{ivpmaxzvpmax}} \]
\[ p_{\text{dg}} = p_{\text{dg}} - p_{\text{stat}} \]
\[ w_{\text{erg}} = 5 \times a_{\text{pal}} (p_{\text{dg}} - p_{\text{stat}}) \]
\[ e_{\text{pip}} = (2 - 2.5 \times \text{pois}) \times p_{\text{ip}} \times p_{\text{ip}} \]
\[ s_{\text{erg}} = e_{\text{pip}} \times (p_{\text{dg}} - p_{\text{stat}}) \]
\[ q_{\text{tot}} = \frac{(\text{eff} \times a_{\text{kmax}} - s_{\text{erg}} - w_{\text{erg}})}{p_{\text{dg}}} \]

320 \text{continue}
\[ i_{\text{ydot}} = i_{\text{ydot}} + 1 \]
if (yi \text{pl} \gt \text{yi} \text{ml}) go to 321
yi \text{pl} = yi \text{ml} + fy_{\text{dot}} \times (yi - yi \text{ml})
\text{yi} = yi \text{pl}
321 \text{continue}
if (abs(yi \text{pl} - yi \text{p0}) \lt .0001) go to 330
yi \text{p0} = yi \text{pl}
if (iy_{\text{dot}} \gt \text{ni} \text{tn}) go to 330
go to 310
c
330 yi ml = yi
yi = yi ml
if (vip \gt \text{vmax}) \text{vmax} = vip
\text{qwaste} = \text{qwaste} + a \times v_{\text{pmax}} \times \text{dt} \]
c
\text{call oscil}(xi, x_{\text{iml}}, dt_{0}, dt, x_{\text{ipl}})
c
\text{yvpl} = yi \text{pl} + x_{\text{ipl}}
\text{ximl} = xi
\text{xi} = x_{\text{ipl}}
\text{yvml} = yv
\text{yv} = yvpl
c
if (float(i-2)/float(ns).ne.float((i-2)/ns)) go to 730
if (nwrite.eq.1) write (3, 30) i, ti, yv, vip, pr, yi, np
      go to 730
c
44444444444444444444444444444 period four
44444444444444444444444444444

c
400 if (np44.ne.100) go to 460
\text{dt} = \text{dt}44
\text{ns} = \text{dt}pr/\text{dt}
np44 = 0
np41 = 41
qpe = .25 * pe
\text{tadv} = 0.
\text{slope} = \text{pmaxg}/qpe
\text{pmt} = \text{pmaxg}
\text{pmrt} = 0.
\text{prt} = 0.
\text{dsq} = 0.
c
pppppppppppppppppppppp determine maximum pressure reached pppppppppppppppppppppppp
do 440 k = 1, 1, 000
\text{itn} = 1
\text{dsqt} = \text{dsq}
\text{prtml} = \text{prt}
\text{pmtml} = \text{pmt}
\text{timl} = \text{ti}
\text{ti} = \text{ti} + \text{dt}
\text{t400} = \text{ti}
\text{t41} = \text{ti} - \text{t40}
\text{tqpe} = qpe - t41
if (\text{tqpe} \lt \text{dt}) go to 450
\text{prt} = \text{prtml} + \text{slope} * \text{dt}
410 \text{prt} = \text{prtml} + \text{slope} * \text{dt}
if (\text{pmrt} \lt \text{prt}) \text{pmrt} = \text{prt}
if (prt.lt.pdg) go to 420
  tadv = tadv + dt
  fradv = tadv / qpe
  pmpd = 2.0 * (prt - pdg) / den
  vp4 = fadv * fradv * cdv * adv * sqrt(pmpd) / ap
  dq = ap * vp4 * dt
  dsq = dsq + dq
  sq = dsq
  dsq = sq
  dqtot = qtot - dsq
  pmrt = pmrt1 - (pmrt1 - pdg) * dsq / qtot
  slope = (pmrt - pmrt1) / (sqpe + dt)
  itn = itn + 1
  if (itn.le.5) go to 410
  go to 430
420
  vp4 = 0.
430
  continue
if (float(k-2)/float(ns).ne.float((k-2)/ns)) go to 440
if (nwrite.eq.1) write (3,30) k, ti, yi, vp4, pr, dqtot, np41
440
  continue
450
  dt = dt4
  np41 = 42
  write (3,30) k, ti, yi, vp4, pmrt, dqtot, np41
460
  continue
  timl = ti
  ti = ti + dt
  c
  anpel = t400 + float(npe) * pe
  anpe2 = anpel + .5 * pe
  if (ti.ge.anpel and ti.lt.anpe2) go to 480
  npe = npe + 1
  to = ti
  tm = ti + .5 * pe
  do 470 in = 1, 50
  ti = ti + dt
  if (ti.ge.tm) go to 475
  if (float(in-2)/float(ns).ne.float((in-2)/ns)) go to 470
  if (nwrite.eq.1) write (3,30) in, ti, yi, hvpi, pr, qtot, np
470
  continue
475
  ti = tm
  go to 485
480
  continue
  c
  pr = pmrt - (pmrt - pdg) * sq / qtot + 1.e-20
  if (pr.le.pdg) go to 485
  pmpd = 2.0 * (pr - pdg) / den
  vp4 = cdv * adv * sqrt(pmpd) / ap
  dq = ap * vp4 * dt
  sq = sq + dq
  hvpi = .5 * vpi
  qdv = qdv + ap * vpi * dt
485
  continue
if (float(i-2)/float(ns).ne.float((i-2)/ns)) go to 490
if (nwrite.eq.1) write (3,30) i, ti, yi, hvpi, pr, qtot, np
490
  continue
  qstop = qtot - 1.e-10
  if (sq.lt.qstop) go to 730
  write ("*", ")'PERIOD FOUR PASSED'
  np = 5
  dt = dt5
  dtp5 = dtp5
  dt50 = 2.0 * al/ac
  t50 = ti
  t60 = ti + dt50
  t4 = ti - t3 - t2 - ti
500 tral=2./(den*ap'al)
re=serg+werg
vp5=-sqrt(re*trag)
p50=pdg
p60=pstat-.5*den*vp5*vp5

xi=ymax
ximl=ymax

do 510 it=1,2000
timl=ti
  ti=ti+dt
  vpi=(ti-t50)*vp5/dt50
  voi=vpi*arpo
  
  if(ti.ge.t60)go to 520
  if(float(it-2)/float(ns).ne.float((it--2)/ns))go to 510
  if(nwrite.eq.1)write(3,30)it,ti,yi,vpi,pr,qtot.np

510 continue

520 vpi=vp5
  vp6=vp5
  kt5=1.+cp+ce
  pr=pstat-.5*den*vpi*vpi
  pr6=pr
    write(3,30)1,ti,dt,vpi,pr,vomax,qp
    write(3,50)
    write(*,'PERIOD FIVE PASSED')
    np=6
    dt=dt6
    dtp=dtp6
    t5=ti-t4-t3-t2-t1
    t60=ti
    yc=0.
goto 730

600 timl=ti
  ti=ti+dt
  tg=ti-t50
  vpin=-vpi
  re=den*vpin*dp/vis
  if(re.gt.2100)go to 610
  f=64./re
  go to 620
610 f=.316/(re**.25)
620 continue
  akt=1.+ctp+cte+f*al/dp
  bb=-9.81*ht/al-.5*vpi*vpi*akt/al
  vpin=bb*dt+vpin
  vpin=vpin
  vpi=-vpin
  voi=vpi*arpo
  pr=pstat-.5*den*vpi*vpi
yc=yc+vpin*dt*ap/ae
call oscil(xi,xim1,dt0,dt,xipl)
yi=xipl
xim1=xi
xi=xipl

if(vpi.ge.0.)go to 640
if(float(i-2)/float(ns).ne.float((i-2)/ns))go to 630
if(nwrite.eq.1)write(3,30)i,ti,yi,vpi,pr,yc,np

continue
go to 730
nc=nc+1
write(*,*),'PERIOD SIX PASSED'
t6=ti-t5-t4-t3-t2-t1
beat=60./(ti-tstart)
if(nc.ge.ncycle)go to 740
tstart=ti
go to 10

if(i.ne.2)go to 710
write (3,47)
write (3,40)cp,cdv,cd,ca,cr,cop,pdgpsi
write (3,46)

710 if(float(i-2)/float(ns).ne.float((i-2)/ns))go to 730
if(nwrite.eq.1)write (3,30)i,ti,yi,vpi,pr,var,np

continue

nc=nc+1
write(*,*),'PERIOD SIX PASSED'
t6=ti-t5-t4-t3-t2-t1
beat=60./(ti-tstart)
if(nc.ge.ncycle)go to 740
tstart=ti
go to 10

write (3,54)
write (3,52)ti,t2,t3,t4,t5,t6,beat
write(3,51)
qwcycle=qwaste*1000.
qtcycle=qtot*1000.
write (3,30)i,ti,yi,vpmax,pr,pmaxg,np
qwlpm=qwaste*beat*1000.
qtlpm=qtot*beat*1000.
write (3,53)
write (3,52)akemax,werg,serg,qwcycle,qtcycle,qwlpm,qtlpm
write (3,43)qwlpm
write (3,44)qtlpm
write (3,45)beat

30 format(i5,5x,5(1pe10.3),i5)
40 format(6f10.3,1pe10.3)
52 format(7(1pe10.3))

43 format(/34h THE WASTE WATER FLOWRATE IS ,f10.3,27h
1LITRES PER MINUTE)
44 format(/34h THE DELIVERY WATER FLOWRATE IS ,f10.3,27h
1LITRES PER MINUTE)
45 format(/34h THE NUMBER OF BEATS IS ,f10.3,27h
1 BEATS PER MINUTE)
46 format(/64h i t(i) y(i) vp(i) pr v
1omax np)
48 format(/65h i t(i) sq vp(i) pr
1qtot np)
49 format(/65h i t(i) period vp(i) pr v
1omax np)
50 format(/65h i t(i) yc vp(i) pr v
1omax np)
51 format(/65h i t(i) yc vpmax pr pm
1axg np)
47 format(/67h cp cdv cd ca cr
1co pdgpsi)
53 format(/67h akemax werg serg qwcycle qtcycle qw
1lpm qtlpm)
Module for computing oscillation of rubber valve flap

Subroutine oscil(zi,zim1,dt0,dt,zip1)

common/osc/vmass, wn, cdampt

rh=dt/dt0
rhpl=rh+1.
cdtv=cdampt*abs(zi-zimi)/vmass
deno=2.+cdtv*rhpl+wn*wn*dt0*dt*rhpl
avib=(2.+2.*rh+cdtv*rhpl)/deno
bvib=2.*rh/deno
zip1=avib*zi-bvib*zim1
return
end

Module for computing drive pipe velocity

Subroutine vpipe

common/gen/ctp, cte, ctde, ctr, ap, arpo, arop, vpi, vpm, vpm1
1 , voi, vmin, vq, waste, pr, dt, pstat
common/dimen/h, dp, tp, al, al, do, dor, de, ddv
common/prop/den, vis, ew, es, pois
common/coeff/cp, cdv, cd, ca, cri, cr2, co

54 format(//6/h) t1 t2 t3 t4 t5 t6
16 beats
stop
end

Module for computing deflection of rubber valve flap

Subroutine ydist(p,y)

common/flap/a,b, tv, er, poir, cdamp, freq

opp=1.+poisr
omp=1.-poisr
tpp=3.+poisr
fpp=5.+poisr
s=b/a
s2=s*s
s4=s2*s2
a4=a*a*a*a
alns=aalog(1./s)
t1=4.*(-s2)+tpp/opp
t2=16.*s2*opp*alns*alns/(omp*(1.-s2))
t3=4.*s2*tpp*alns/omp
t4=(1.-s4)+fpp/opp
c1=p*a4*3.*opp*omp/(ertv*tv*tv*16.)
y=c1*(t1+t2-t3-t4)
return
end
if (reo.gt.2100.) go to 1030
fo=64./reo
go to 1040
1030 fo=.316/(reo**.25)
1040 continue

akt=1.*c+co+ctp+cte+ctda+ctr+aop*aop*f*a1/dp
1 +fo*alc/do
bb=.5*voi*voi*akt/al
vpi=(9.81*h/al_bb)*dt+vpim1
voi=vpi*arpo
pr=pstat-.5*den*vpi*vpi
return
end