Injectors for Pressure Control in PUR Mixing

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ABSTRACT

The injectors have a fundamental role in the Polyurethane (PUR) mixing. The purpose of the Paper is to explain why the pressure at the injector is so important and how to set and control it. The Paper does not investigate the possible forms and shapes of injectors or mixing chambers for optimising the mixing process. Shapes and forms are the “tricks “ that the different producers of mixing heads know and develop and are an important part of their skill.

THE STATE OF THE ART

To mix two reactant liquids, like those forming the PUR, there are in general three basic mixing technologies.

1) Static mixing*:* It is performed by shearing, dividing and whirling the streams by means of the turbulence induced into the two liquids flowing along a channel in which many sharp obstacles are inserted (*Figure 1*)

2) Low pressure mixing: It is performed putting in common the two liquid components into a mixing chamber in which a mechanical mixer is rotating at high speed so to generate shearing, dividing and turbulence sufficiently to mix the two (or more) liquids. The mixer and the mixing chamber are shaped with pins or crests and grooves to create the necessary actions within the liquid flow as to realize the mixing effect. (*Figures 2 & 3*)

In both these techniques the pressure of the liquids is not important and the mixing heads are provided by injectors just to open or close the streams and to properly compensate the small pressure drop during the re-circulation or the mixing.

3) High pressure mixing: The high pressure mixing is quite different as there are no mechanical mixers: the mixing energy and turbulence is generated by the impingement of the jets of liquid. Proper injectors shall generate jets with high kinetic energy. (*Figures 4 & 5*)

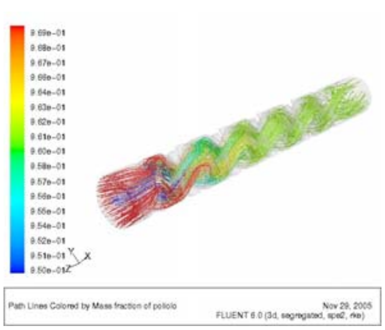


Figure 1

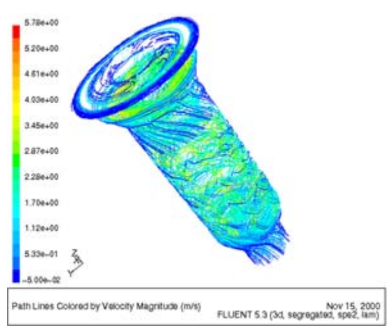


Figure 2

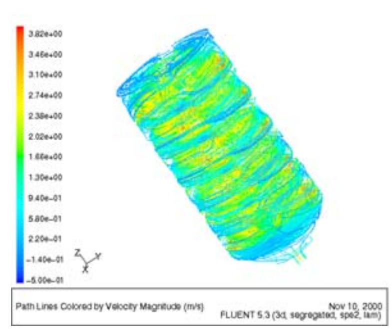


Figure 3

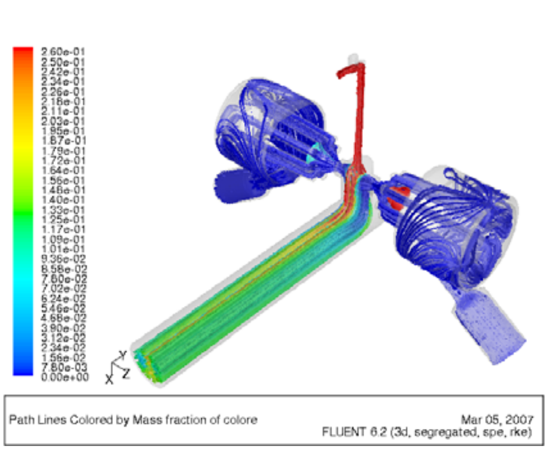


Figure 4

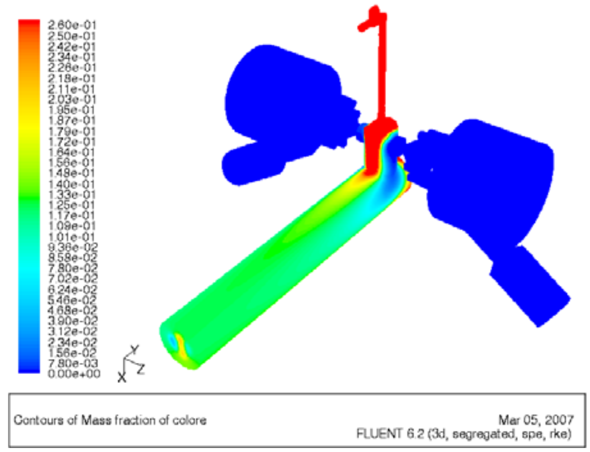


Figure 5

In general the jets are directed "head-on," one against the other in a mixing chamber. The jets collide together or/and onto the surrounding liquid stream or against the walls inside a small mixing chamber. The turbulence caused by the jets facilitates a very fast and profound mixing. The injectors and the related pressure play a fundamental role. The lack of a mechanical mixer allows the possibility to use fast reacting materials and to avoid the use of solvents to keep the mixer clean.

Importance of the pressure setting

The importance of the pressure setting at the injector inlet is dependent on some basic premises; the high pressure mixing requires fast and efficient jets. To convert pressure into kinetic energy normally the injectors have restrictions.
The jets are formed at the outlet of the restrictions. The higher the fluid pressure is at the inlet, the faster the velocity of the jets.
The basic relation for converting energy for the injectors is the Bernoulli's equation

$$P = \frac{1}{2}\rho V^2$$

EFFICIENT IMPINGEMENT

There is high level of mixing when the conversion pressure-jet energy is efficient and the mixing chamber shape is suitable towards the front of the impingement. The setting and the control of the inlet pressure is fundamental for the best mixing performance. There are three critical parameters to be pressure set.

Setting the impingement front

The two (or more) jets shall collide or impinge in the most efficient way inside the mixing chamber. It is easy to show from experimental tests that the best mixing efficiency occurs when the impinging front is maintained in the middle of the cylindrical chamber. Note that the collision of the two jets maintains the momentum in spite of the energy. (*Figure 6*)

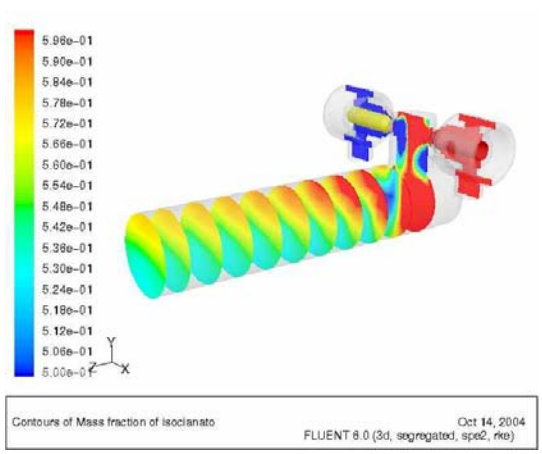


Figure 6

In addition we have to consider that each jet dissipates energy (speed) along its path in ratio with the distance from the injector. It is easy to see that the position of the impact of the two jets within the mixing chamber depends on their reciprocal specific energy (i.e. velocity and mass flow). The impingement layer is in the middle of the mixing chamber when

$$\rho_1 Q_1 V_1 = \rho_2 Q_2 V_2$$

Consider Iso and Polyol metered in ratio 1 to 1 with the same pressure at the injectors.
Within the mixing chamber we will have the jet of the Polyol travelling a little faster ($\rho_p < \rho_I$), with the jet of the Iso travelling a bit slower and the collision layer in the middle of the mixing chamber.
Consider now the two jets from the injectors with the same speed, as the Iso is heavier ($\rho_i > \rho_p$), it will "win" during the collision and the impingement front results shifted from the middle of the mixing chamber toward the Polyol side.

In case of excess Iso, the collision front will be heavily shifted and the mixing effect becomes poorer
On the other hand, when we mix a filled Polyol in excess against the Iso, the mixing front will be shifted towards the Iso side.

So when the ratio is not 1 to 1, it is worth compensating for the deficiency of momentum in the poorer stream by increasing its pressure. It is also evident that jets not colliding in absolutely opposing directions (therefore inclined injectors) are less efficient when the ratio is far from 1 to 1

Compensation of the viscosity

The Polyol normally has a higher viscosity than the Isocyanate. Moreover the pressure of the two components is measured close to the metering pump or along the piping. As a result of this, the real pressure at the injector ready to be transformed into kinetic energy is not what is read at the pressure transducer, but is lower - due to the loss of pressure caused by the viscous forces of the liquid moving along the piping. This pressure drop depends on the size of the piping, the temperature of the liquid and its flow rate. In general it is not necessary to entirely compensate these losses of pressure because the higher the flow rate, the higher the energy available will be for mixing. (*fig. 7*)

Compensation of the so called Pre-flows

The pre flows are due to differences in ratio of the two components during the fast transition generated by the opening of the spool or of the injectors. The pre-flows are strictly related to the function of the high pressure mix-head.
In general all the high pressure mixing is preceded by a high pressure re-circulation that usually is performed by a grooved spool. The grooves (one for each injector) can be shifted from the position that provides re-circulation to a position retracted that provides mixing. The spool, when closed forward, moves the grooves in front of the injectors so to re-circulate the streams back to the return line. When the mixing spool retracts flows are shifted from re-circulation to mixing.
During the shifting the front section of the spool separating the grooves passes in front of the injectors closing them for a very short transient. The spool is moved by its control as fast as possible but, during the transient, the injectors are blocked by the passage in front. The streams throughout the injectors are suddenly stopped for some milliseconds during the switching from high pressure re-circulation to mixing and vice versa.

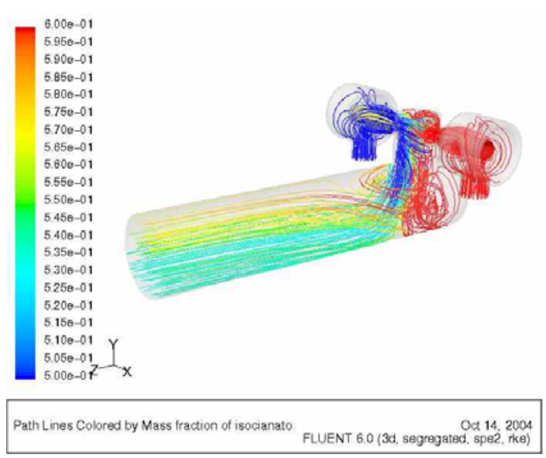


Figure 7

The metering systems in general do not react to the sudden blocking of the streams due to the inertia of the mechanical and fluid components so all the volume of the flow that cannot pass is accumulated by the elasticity (the Bulk modulus) of the delivery system (Piping, hoses, compressibility of the resin act together like an accumulator).
The liquid flow is converted into a sudden pressure drop in ratio with the elasticity of the delivery system and liquid.
When the injector front re-opens, this accumulated volume is discharged in a fast transient.

The problem is how to maintain the ratio also during the fast discharge.

If both the accumulated volumes are in a reasonably low quantity and more or less in proportion, during the discharge the liquids will maintain the desired ratio.
When the volumes are larger and the accumulation not proportional, during the transient the ratio is not maintained and the pre-flows are seen as a spot of poorly mixed PUR with a different look and characteristics (poor) inside a homogenous mix.

The compensation of the pre-flows is very important but not so easy to set and a high level of expertise is necessary in setting the foaming parameters and cancelling the pre-flows. For the mix heads without grooves, the control of the re-circulation and of the switching from re-circulation to mixing shall be performed by the injectors that must control both the diverting of the flows and the pressure set and in general this control is difficult to operate and set.

SIMPLE MECHANICAL INJECTORS AND THEIR CONTROL

Orifice nozzles

A simple injector is shaped as an orifice nozzle i.e. a sudden restriction of the fluid passage. The simplest form is circular with sharp edges. Through the nozzle the pressure is immediately converted into velocity and the outgoing jet is a straight beam that (in open air) can remain coherent for meters. The relations between pressure and speed is seen in Bernoulli's formula

$$V = K * \sqrt{\frac{2\Delta p}{\rho}}$$

To get good performances usually V≥100 mt/sec i.e. $P_2 \geq 120 - 140$ bar is requested
The orifice nozzles are very efficient and economic but, as the metering unit controls only the flow rate, the setting of the pressure through the orifice is very difficult and the shape and dimensions of the injector section area are highly critical.

Differences of hundredths of a millimetre and errors in the shape of the hole can result in high differences in the pressure set. Figure 8 below shows the relation between the flow Q and the nozzle diameter

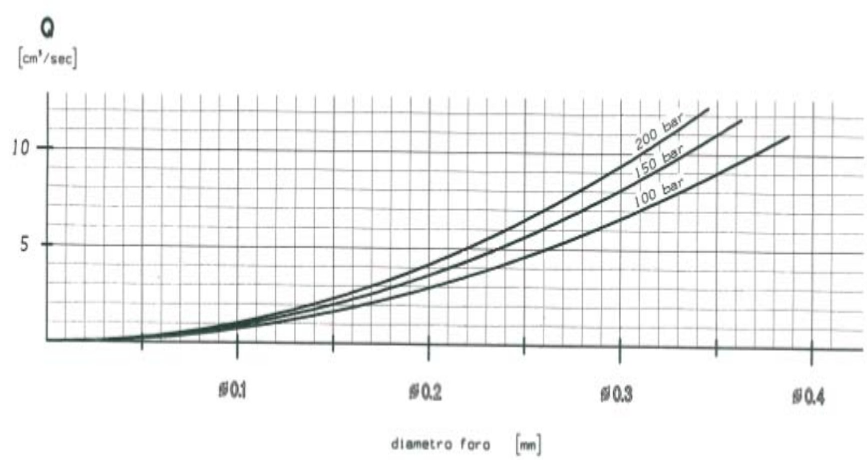
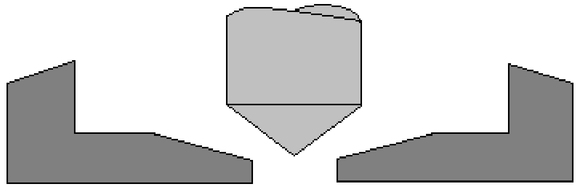


Figure 8 - Pressures, diameters and flow rates for the simple round orifices.

Nozzles with fix settable restriction

The evident difficulty in setting the pressure at a stated flow rate requires having the possibility to modify (and to complicate) the orifice section slightly by using a system that makes the final restriction settable.
The simplest solution is to maintain the round orifice and fit into its centre a pin with conical shape. (*Figure 9*)



(*Figure 9*)

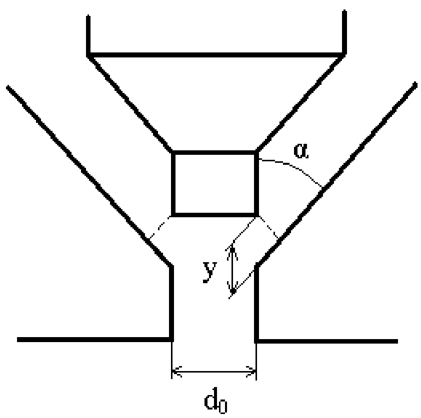
By moving the pin forwards or backwards, the restricted section can be set to the desired pressure. The flow equation is

$$Q = KA(y) * \sqrt{\frac{2\Delta p}{\rho}} \qquad \Delta p = \frac{\rho}{2} \frac{Q^2}{K^2 A^2(y)}$$

Where:
y indicates a variable axial setting (displacement) of the needle
K is a coefficient.

Linearization of the needle nozzle

The best performances in term of mixing are instead given by a nozzle made with a reversed conical female and a cylindrical needle for which both needle and conical female have the same final diameter For this configuration note (*Figure 10*) that small opening displacement of the needle front generates the restricted section given by



(*Figure 10*)

$$A(y) = d\pi \sin(\alpha) y$$

The nozzle with a settable (but fixed after set) central pin is quite common but still does not give a high performance as it is very sensitive to uncontrolled variations of flows and pressures but especially to some accumulated solid that can vary the restricted area of the nozzle. When the flow rate shall be varied in a controlled manner for necessity of changing the ratio or/and the overall throughput flow shot by shot these nozzles are inadequate.

Nozzle with self setting restriction

A smarter but still simple solution is to combine a preliminary setting and a self adaptation of the needle against the flow rate. If we consider the geometry shown above (i.e.) conical reversed female and cylindrical pin, we can imagine to give the pin the possibility to be displaced by the pressure of the liquid component and to compensate the increasing the flow rate by a reasonable building in pressure.

A typical form is an injector with reversed conical nozzle and conical front needle provided with sliding cylindrical surfaces so the needle retracts with increasing pressure.
On the rear end of the needle a spring with settable pre-charge and correct stiffness pushes the needle against the nozzle.
In this way the injector is normally closed since the force caused by the pressure is lower than the spring pre-charge.
When the component pressure exceeds the set, the needle opens.

The system is simple and self adjusting i.e. the pressure at the needle causes the opening of the restriction up to the position in which the flow rate delivered by the pump is equal to the flow rate of the jet.
During the transient a small part of the flow rate is accumulated in the elasticity of the delivery line and in the liquid.

Typical equations of the self compensating system needle -spring

The system is self compensating. As the flow rate increases, also the pressure increases, the needle is pushed back with higher force, compressing the spring further (and thus opening the needle further) and as a consequence, the flow of the jet also increases. The stability is given by the increasing pressure against the increasing flow rate and by the shape of the nozzle that dissipates energy. The "static" equations of the system are:

$$1)\quad Q_i(y) = C_n A(y) \sqrt{\frac{2}{\rho} P_i}$$

Where:
Qj(y) = jet flow rate (depending from pressure and y i.e. the opening of the injector)
y = displacement of the needle
Cn = form factor of the jet (usually) 1 < Cn < 0,8 (we can consider = 1 for simplicity)
A(y) = jet flowing section (It is normally a circular section)
ρ = specific mass of the component
Pi = pressure in the injector

If we consider the nozzle as a reverse conical with α semi-angle and the needle cylindrical, the opening section A(y) is a conical surface that we can express in a simplified way as follows

$$2)\qquad A(y) = d_0 \pi \sin(\alpha) y$$

Where:
d0 is the diameter of the nozzle
α is the angle between the conical surface of the needle and its axis

$$Q_i(y) = d_0 \pi \sin(\alpha) y \sqrt{\frac{2}{\rho} P_i}$$

The equilibrium of the spring against the pressure force is

$$3)\qquad P_i A_u = F + Ky + Kz$$

Where:
Pi = pressure in the injector
Au = section of the needle
Fo = spring pre-charge
yK = force due to the spring
F = force due to control action

So

$$Y = \frac{P_i A_u - F - Kz}{K}$$

Taking in account just small variations around a working position 0 we can convert the system to linear equations

$$\Delta Y = \frac{\Delta P_i A_u - F - Kz}{K}$$

$$\Delta Q_i = d_0 \pi \sin(\alpha) \sqrt{\frac{2}{\rho}} \sqrt{P_{i0}} \Delta Y + d_0 \pi \sin(\alpha) \sqrt{\frac{2}{\rho}} \frac{y_0}{2\sqrt{P_{i0}}} \Delta P_i$$

$$\Delta Q_i = d_0 \pi \sin(\alpha)\sqrt{\frac{2}{\rho}}\sqrt{P_{i0}}\Delta Y + d_0 \pi \sin(\alpha)\sqrt{\frac{2}{\rho}}\sqrt{P_{i0}}\frac{y_0}{2P_{i0}}\Delta P_i$$

$$\Delta Q_i = C_p d_0 \Delta y + C_p d_0 C_{eq} \Delta P_i$$

Where:

$$C_p = \pi \sin(\alpha)\sqrt{\frac{2}{\rho}}\sqrt{P_{i0}}$$

$$C_{eq} = \frac{y_0}{2P_{i0}}$$

ρ = is the density of the material
y_0 = needle's position of equilibrium
P_{i0} = pressure of equilibrium in the injector

Application of seals

For this type of injector it is also convenient to have the possibility to apply seals to the shaft that transfers the movement of the needle to the spring, so the spring is assembled on a dry side.
The friction force generated by the seals is proportional to the pressure and to the length of the seal. The pressure force that opens the needle is proportional to the section so the effect of hysteresis due to the seals is reduced in ratio with wider sections.

CONTROL OF THE PRESSURE AT THE INJECTORS WITH ACTIVE SYSTEMS

When a great variation of ratio and flow is requested from shot to shot, it is fundamental to control and maintain the pressure at the inlet of the injector to guarantee:

- sufficient energy of the impinging jets,
- properly control the impingement front,
- proper compensation of the pre-flows.

Basic types of actuators for the active injectors

We can classify the actuators in 2 basic types:

- actuators to control indirectly the force on the needle.
- actuators to control directly the force on the needle.
- actuators to control the position of the needle

Very few actuators control the section of the orifice and they are not mentioned here.

The first type is described above i.e. an injector settable by spring tightening and devices to modify the pressure on the spring. (*Figure 11*)

The second is an injector controlled only by the pressure of some fluid (oil or air) that generates the force necessary to set the needle. (*Figure 12*)

The third is an injector where the actuator directly controls the position of the needle that is controlled in position. (*Figure 13*)

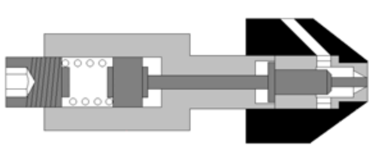


Figure 11

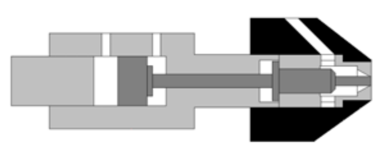


Figure 12

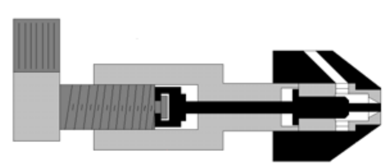


Figure 13

Pressure control system in open and closed loop

There are two main categories of active control systems offered by the producers of metering units for the mixing pressures:

- active system in open loop
- active systems in closed loop

The system classified as open loop merely preset the position or the force at desired values chosen with software tables.
The closed loop systems measure the pressure close to the injector or close to the pump, control the variation of force or the position to set and maintain the pressure for changes in flow rate and or disturbances at the injector.
All utilise different types of actuators to control the restriction of the injector and , indirectly, the pressure.

DYNAMIC EQUATIONS AND THEIR LINEARIZATION WITH THE LAPLACE TRANSFORM

We summarize here some elements of the theory of control systems and discuss the stability and control performances of three different types of controlled injectors.

Schematisation of the systems

For the proceeding of the Paper we use the typical approach of the control system theory:

- Schematisation of the system by means of differential equation
- Linearization of the equations around a set working condition
- Transform of the equation through the Laplace transform into algebraic linear
- Analysis of the configurations by means of schematic diagrams
- Analysis of the frequency response by the use of Bode diagrams
- Conclusions and suggestions

<u>*Schematisation of the system pump - piping – injector by means of differential equation*</u>

The schematisation adopted is the following (*Figure 14*)

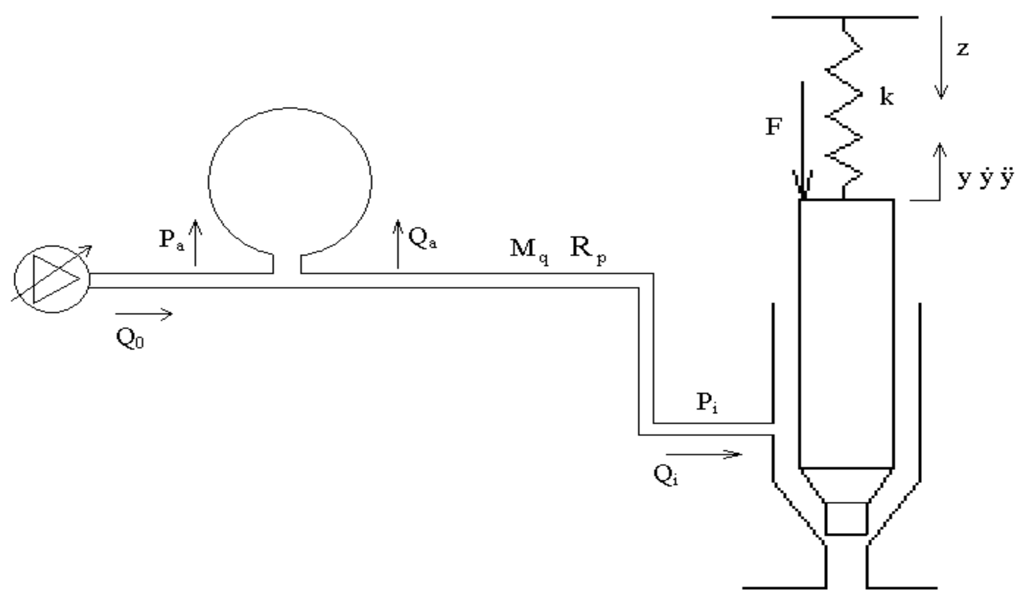


Figure 14

<u>*Variables*</u>

Q_0 resin flow rate (fix)
Q_a volume accumulated along the piping
Q_i flow passing through the injector
Y displacement of the needle
F control force of the needle
P_a pressure at the pump delivery
P_i pressure in the injector
A_i restricted section of the injector

Constants and values taken as example

Q_0	flow rate at the pump	350 cc/s	0.00035 m^3/s
ρ	resin specific mass	1,000 g/l	1,000 Kg/m^3
L	piping length	15,000 mm	15 m
d_p	piping diameter	20 mm	0.02 m
A_p	piping section	314.2 mm^2	0.000314 m^2
V_0	piping volume	4.7 l	0.0047 m^3
$1/\beta_a$	piping bulk modulus	5 l/(100 l 100 bar)	5*10^(-9) m^2/N
R_p	piping hydraulic resistance	19 bar/350 cc/s	5,428,571,429 $Pa*s/m^3$
F_0	pre-charge of the spring	10 Kg	100 N
M_q	component equivalent inertia	47,746,482 Kg/m^4	47,746,482 Kg/m^4
d_0	nozzle and tip needle diameter	2 mm	0.002 m
α	angle of the nozzle	60 °	1.04 rad
A_u	section of the needle	19.6 mm^2	0.0000196 m^2
d_u	needle control diameter	5 mm	0.005 m
K	stiffness of the spring	25 Kg/mm	250,000 N/m

Relations between constants:

$$A_p = \pi \frac{d_p^2}{4}$$

$$V_0 = A_p L$$

$$A_u = \pi \frac{d_u^2}{4}$$

$$M_q = \frac{\rho L}{A_p}$$

Assumptions:

- The pumping system delivering the flow rate is infinitely stiff i.e. the metered flow rate does not vary when the pressure of the liquid is modified. This is verified when the volumetric efficiency of the pump is good and the driving motor is oversized
- The variations of pressure along the piping are instantaneous.
- The elasticity of the piping and the compressibility of the liquid accumulate volume for pressure variations
- We consider only small variations around set working conditions

Equations for the dynamic equilibrium of the system

$$Q_a = \frac{V_0}{\beta_a} \dot{P}_a$$ Flow accumulated by compressibility of the piping plus resin

$$Q_0 = Q_a + Q_i$$ Equilibrium of flows

$$P_a = P_i + Q_i R_p + \dot{Q}_i M_q$$ Dynamic equilibrium of the liquid along the piping

$$A_i = d_0 \pi y \sin(\alpha)$$ Restricted section of the injector

$$Q_i = A_i \sqrt{\frac{2}{\rho} P_i}$$ Bernoulli's equation

$$kz + ky + F = P_i A_u$$ Forces equilibrium at the needle

After the necessary linearization and simplifications, the system of linear differential equations is:

$$Q_a = \frac{V_0}{\beta}\dot{P}_a$$
$$Q_0 = Q_i + Q_a$$
$$Q_i = C_p d_0 y + C_p d_0 C_{eq} P_i$$
$$P_a = P_i + Q_i R_p + \dot{Q}_i M_q$$
$$ky + kz + F = P_i A_u$$

Where:

$$C_p = \pi \sin(\alpha)\sqrt{\frac{2}{\rho}}\sqrt{P_{i0}}$$

$$C_{eq} = \frac{y_0}{2P_{i0}}$$

LAPLACE TRANSFORM

Applying the Laplace transform, ignoring the starting conditions and considering small variations around the equilibrium, it is possible to express the system with linear algebraic equations

$$Q_a = \frac{V_0}{\beta} s P_a$$
$$Q_0 = Q_i + Q_a$$
$$Q_i = C_p d_0 y + C_p d_0 C_{eq} P_i$$
$$P_a = P_i + Q_i \left(R_p + s M_q\right)$$
$$ky + kz + F = P_i A_u$$

BLOCK DIAGRAMS

The equation system can easily be represented by means of a block diagram where the symbols are typical of the control theory

Block diagram for the injectors controlled by direct or indirect force

Block diagram A (*Figure 15*)

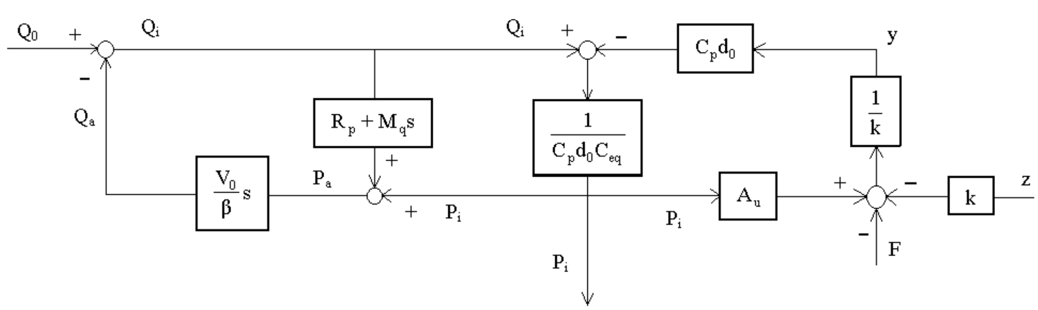


Figure 15

Block diagram for the injectors controlled by the needle position

Block diagram B (*Figure 16*)

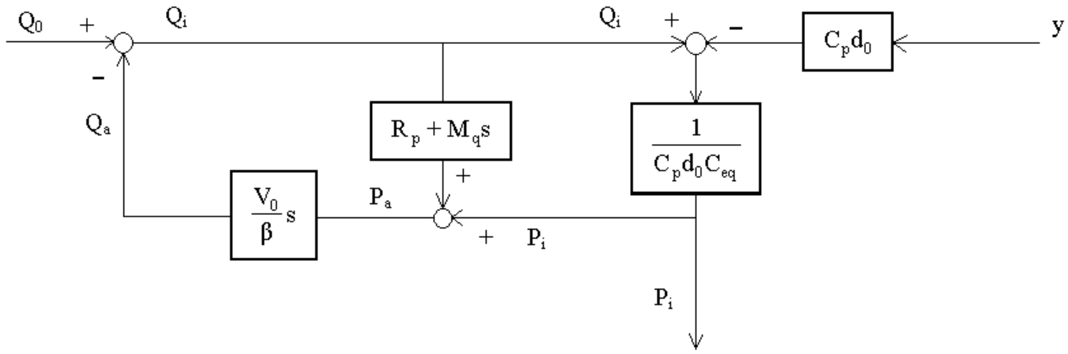


Figure 16

Transfer functions and Bode diagrams *(for the injectors controlled by direct force)*

With reference to the block diagram A (Fig. 15) and the set of five equations from which it is deriving, when the lone force is applied to the needle we can see with the enclosed equation that the solution is depending from two different fix parameters.

E0) $$P_i \frac{1+R_p\frac{V_0}{\beta}s+M_q\frac{V_0}{\beta}s^2+\frac{V_0}{\beta}\frac{s}{C_p d_0 C_{eq}}}{1+R_p\frac{V_0}{\beta}s+M_q\frac{V_0}{\beta}s^2}\left(C_p d_0 C_{eq}\right)=\frac{Q_0}{1+R_p\frac{V_0}{\beta}s+M_q\frac{V_0}{\beta}s^2}-C_p d_0 C_{eq} y$$

INJECTORS CONTROLLED BY FORCE: COMMENTS AND CONCLUSIONS

The injectors controlled by spring are the easiest to fabricate.

Open loop control

They are usually composed by a compressed air loaded piston that directly controls the force on the needle. The piston can be a real circular piston with seals or a membrane or a bellow actuator.

The main advantage is the possibility to use the pressure of the air to control the pressures at the injectors

- compressed air is cheap, clean and not disturbing when leaking.
- pressure reducers are cheap and can be chosen in a wide variety.

Even the injector case is the cheapest: usually done in aluminium with small hoses to deliver the air pressure. The pressure transducers or the controlled valves to set the air pressure are also cheap.

From the simplified equation F= Pi/Au it is evident that, if the K spring stiffness is negligible and also the damping of the piston and its inertia are negligible, the pressure at the injector should be equal to the force that controls the piston. But it is also evident from the equation E0) that, for small variation, the system is "free" i.e. quite close to the oscillation.

We can use the block diagram A for further analysis.

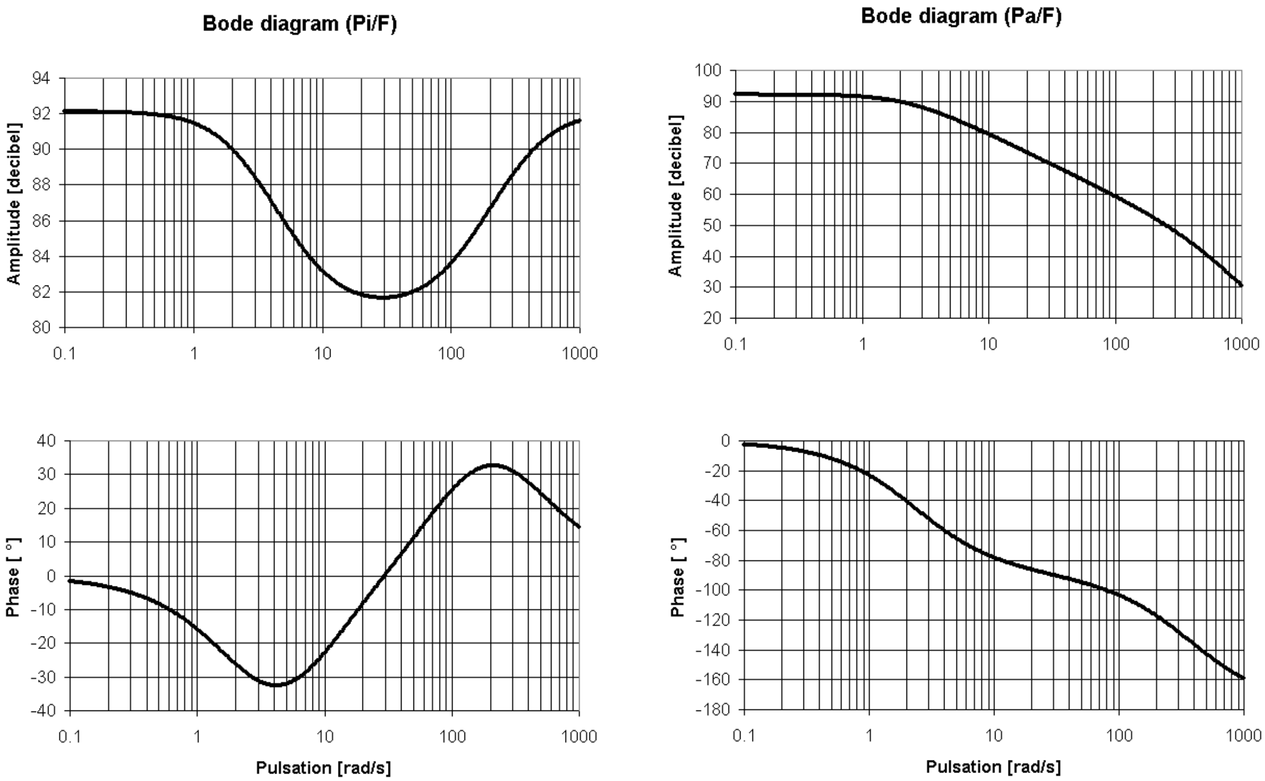
P_i/ F *Pressure at the injector vs Force at the needle* – Ref. to block diagram A (Figure 15)

E1) $$\frac{P_i(s)}{F(s)}=\frac{1}{kC_{eq}+A_u}\frac{s^2\frac{V_0}{\beta}M_q+s\frac{V_0}{\beta}R_p+1}{s^2\frac{V_0}{\beta}M_q+s\frac{V_0}{\beta}\left(R_p+k/\left(C_p d_0 A_u+C_p d_0 C_{eq}k\right)\right)+1}$$

P_a / F _<u>*Pressure at the injector vs Force at the needle*</u> – Ref. to block diagram A (Figure 15)

E2) $$\frac{P_a(s)}{F(s)} = \frac{1}{C_{eq}k + A_u} \frac{1}{s^2 \frac{V_0}{\beta} M_q + s \frac{V_0}{\beta} \left(R_p + k / \left(C_p d_0 A_u + C_p d_0 C_{eq} k\right)\right) + 1}$$

E1) E2)



INJECTORS CONTROLLED BY FORCE WITH COMPENSATION SPRING. COMMENTS AND CONCLUSIONS

<u>Open loop control</u>

The common use of membranes, bellows, dumpers, throttling, spiral springs on these types of controlled injectors on the PUR market, shows the necessity to stabilize them by means of spring reaction, friction avoiding (membrane, bellows) or dumpers (throttling, air spillage).

As the main advantage is the cost and the easy application, the main problems of these injectors are :

- the dimensions
- the irregularity of functioning (hysteresis) due to the friction caused by seals and movable parts
- the low stability in closed loop and the lack of reaction force.

The wide application of devices without friction and by the use of dampers and springs demonstrate the difficulties encountered by the producers. So, in general, an open loop control or a feed forward control is preferred for this system.
It is convenient to use low stiffness springs, not to increase too much the size of the actuator.

The error introduced by the friction is reduced by the use of the pre-set pressure because the opening and closing of the spool blinds the orifice and causes the friction to be always one way.
Also the disturbances of pressure coming from the opposite impinging jet is quite disturbing and causing oscillations if the injectors are wide or the pressures are high.

Closed loop control

The application of the closed loop control for this type of injector is very easy and cheap. It is enough to provide a controlled pressure reducer. From the Bode diagrams it is easy to see that the system has a redundancy caused by the mass of the resin and the compressibility of the delivery line.

To prevent oscillation and hysteresis the so-called “feed forward” control is preferred, and also works properly.
It is possible to stabilise the system for low values of the gain, but in this way the system is not reacting to fast changes of the pressure outside the “feed forward”.

In closed loop the friction is enhanced by the system that begins to jump from one pressure value to the other around the friction value so it is worth to stabilize it by thresholds of dead control or other non linear control tricks.

In conclusion

- this system is simple and cheap to apply and maintain:
- it is poorly stable
- for higher stability it is suggestible to read the pressure at the pump and to use spring reaction and dumpers together
- the system is not precise and sensitive to the heavy transients
- it shows a specific hysteresis due to friction effects during the control in closed loop.

Transfer functions and Bode diagrams

(for the injectors controlled by indirect force with spring) - Ref. to block diagram A (Figure 15)

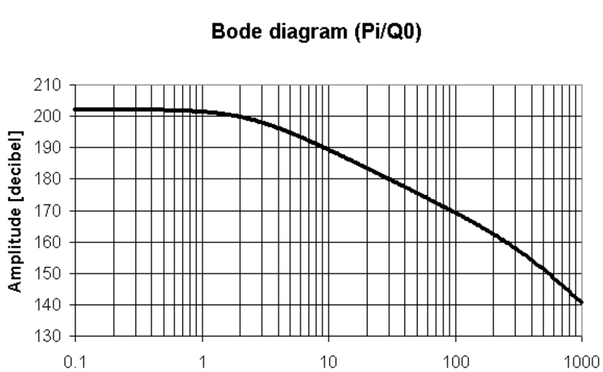
P_i/Qo *Pressure at the injector vs pump delivery rate with spring*

E3) $$\frac{P_i(s)}{Q(s)} = \frac{\dfrac{k}{\left(kC_p d_0 C_{eq} + C_p d_0 A_u\right)}}{s^2 \dfrac{V_0}{\beta} M_q + s \dfrac{V_0}{\beta}\left(R_p + k/\left(kC_p d_0 C_{eq} + C_p d_0 A_u\right)\right) + 1}$$

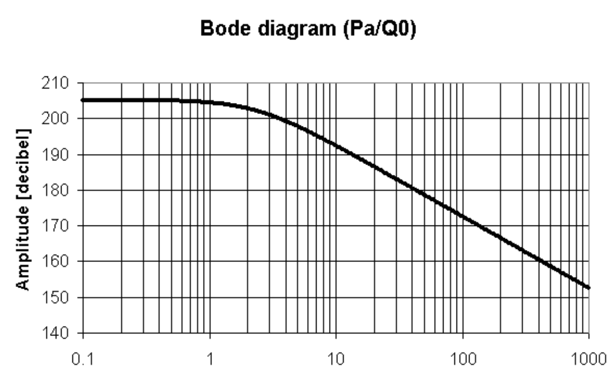
P_a/Qo *Pressure at the pump vs pump delivery rate with spring*

E4) $$\frac{P_a(s)}{Q(s)} = \frac{sM_q + R_p + k/\left(C_p d_0 A_u + C_p d_0 C_{eq} k\right)}{s^2 \dfrac{V_0}{\beta} M_q + s \dfrac{V_0}{\beta}\left(R_p + k/\left(C_p d_0 A_u + C_p d_0 C_{eq} k\right)\right) + 1}$$

E3)



E4)



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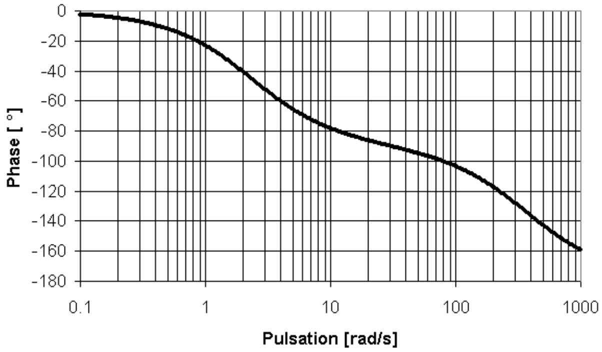
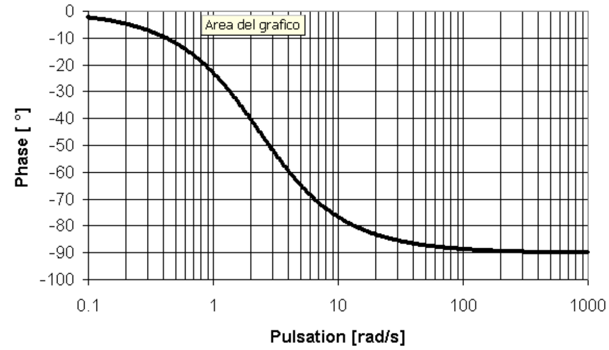




With reference to block diagram A (Figure 15):

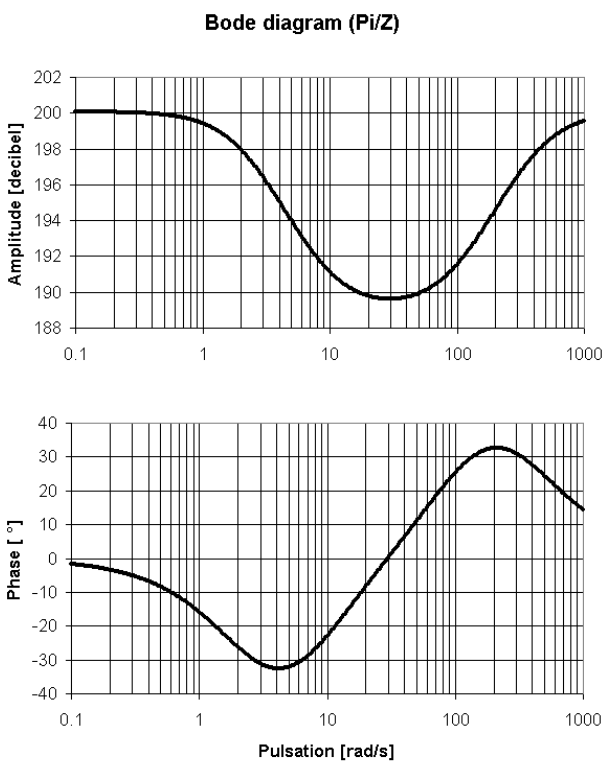
P_i/ z *Pressure at the injector vs spring force setting at the needle*

$$\text{E5)}\quad \frac{P_i(s)}{z(s)} = \frac{P_i(s)}{F(s)}k = \frac{k}{kC_{eq}+A_u}\,\frac{s^2\frac{V_0}{\beta}M_q + s\frac{V_0}{\beta}R_p + 1}{s^2\frac{V_0}{\beta}M_q + s\frac{V_0}{\beta}\left(R_p + k/\left(C_pd_0A_u + C_pd_0C_{eq}k\right)\right)+1}$$

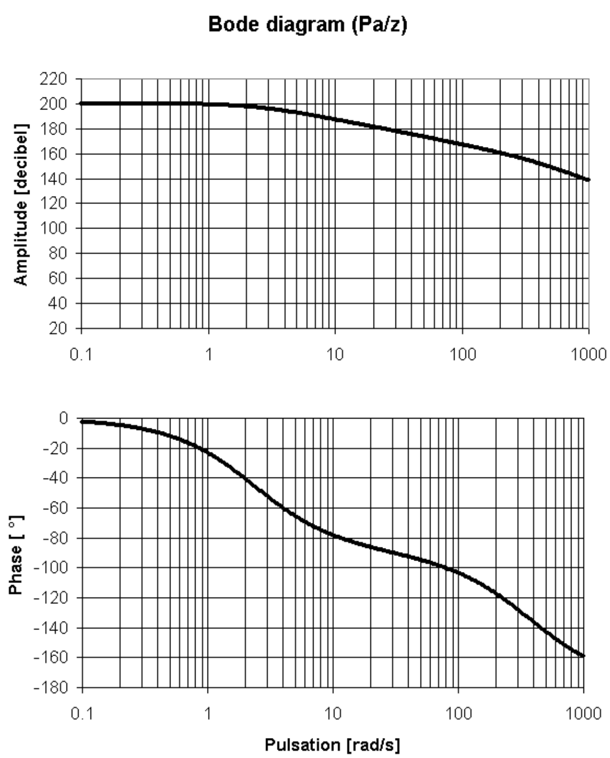
P_a/ z *Pressure at the injector vs spring force setting at the needle*

$$\text{E6)}\quad \frac{P_a(s)}{z(s)} = \frac{P_a(s)}{F(s)}k = \frac{k}{C_{eq}k+A_u}\,\frac{1}{s^2\frac{V_0}{\beta}M_q + s\frac{V_0}{\beta}\left(R_p + k/\left(C_pd_0A_u + C_pd_0C_{eq}k\right)\right)+1}$$

E5)



E6)



INJECTORS CONTROLLED BY SPRING: COMMENTS AND CONCLUSIONS

The injectors controlled by spring are the most common and easy to fabricate.

Open loop control

They perform well at stated conditions and compensate properly the accumulation of dirt at the orifice. They do not compensate at all disturbances coming from the friction of the needle during its movement along its bore.

With reference to the equations E3) the static performance can be expressed considering S = 0
The static behaviour is expressed by

$$\frac{P_i(0)}{Q(0)} = \frac{k}{kC_p d_0 C_{eq} + C_p d_0 A_u}$$

It is evident the convenience of using low stiffness springs to try to compensate as much as possible the flow variation maintaining the pressure into reasonable thresholds.
The delta force due to friction or presence of seals is not compensated at all by the spring; so the this type of control does not reduce the delta pressure due to friction that is normally between 5 % and 10% of the pressure set.

As it is easy to see in static conditions possible occlusions of the injectors are efficiently compensated by application of low stiffness spring and by the use of wider nozzle diameter. The value of the working pressure is not influencing the static behaviour

In dynamic conditions, as well low spring stiffness, wider diameters of the nozzle better compensates the disturbances.

When analysing the effect of force disturbances on the needle due e.g. to friction, in static conditions, they are better mitigated by stiff springs and by wider needle sections.

Also the disturbances of pressure coming from the opposite impinging jet is only partially reduced by the spring.
It is evident that in closed loop the friction is enhanced by the system that begins to jump from one pressure value to the other around the friction value.

Closed loop control

The application of the closed loop control for this type of injector is easy: it is enough to provide a device that presses the spring adjusting the set of the spring in proportion to the difference from the actual pressure value at the injector and the pressure reference. From the Bode diagrams it is easy to see that the system is stable for suitable values of gain and that the system is not fast reacting to fast changes of the pressure.

It is fast to compensate the build up of dirt in the orifice (changing of the restriction section).

It does not react fast to the force disturbances due to the effect of friction and the effect of the counter-pressure due to the second impinging jet.

The system tends to oscillate or “jump” between the friction differences during force increasing and force decreasing to reach the set value. The lower is the stiffness of the spring the higher are the effects described.

In conclusion

- this system is simple to apply
- it is quite stable with real poles well separated
- it is not fast and so it does compensate properly and with stability the pressure after the transient
- shows a specific hysteresis due to friction effects during the control in closed loop
- lowering the spring stiffness tends to reduce the system damping.

Transfer functions and Bode diagrams
(for the injectors controlled by displacement of the needle y)

With reference to block diagram B (Figure 16)

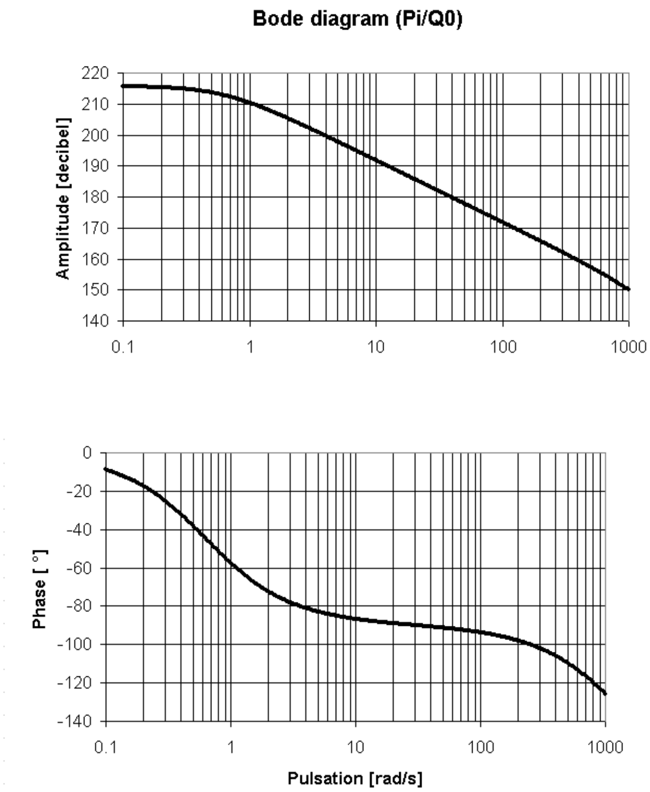
P_i/ Q_o *Pressure at the injector vs delivery of the pump*

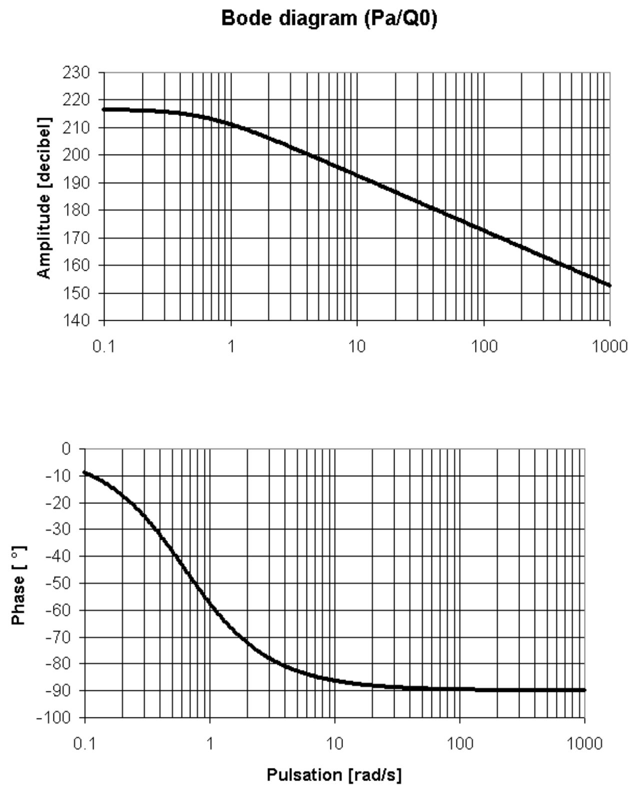
E7) $$\frac{P_i(s)}{Q_0(s)} = \frac{1}{C_p d_0 C_{eq}} \frac{1}{s^2 \frac{V_0}{\beta} M_q + s\frac{V_0}{\beta}\left(R_p + 1/\left(C_p d_0 C_{eq}\right)\right) + 1}$$

P_a / Q_o *Pressure at the pump vs delivery of the pump*

$$\text{E8)}\quad \frac{P_a(s)}{Q_0(s)} = \frac{sM_q + R_p + 1/\left(C_p d_0 C_{eq}\right)}{s^2 \frac{V_0}{\beta} M_q + s\frac{V_0}{\beta}\left(R_p + 1/\left(C_p d_0 C_{eq}\right)\right) + 1}$$

E7) E8)





With reference to block diagram B (Figure 16)

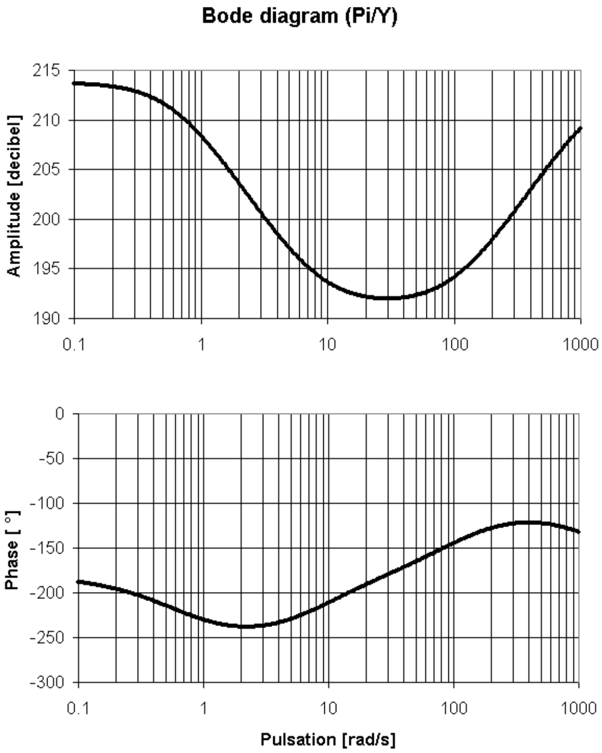
P_i / y *Pressure at the injector vs setting of the needle*

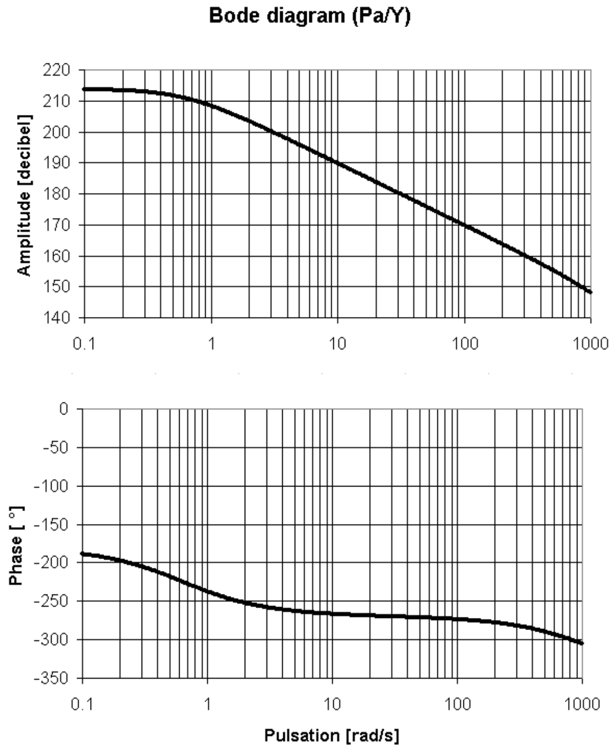
$$\text{E9)}\quad \frac{P_i(s)}{Y(s)} = -\frac{1}{C_{eq}} \frac{s^2 \frac{V_0}{\beta} M_q + s\frac{V_0}{\beta} R_p + 1}{s^2 \frac{V_0}{\beta} M_q + s\frac{V_0}{\beta}\left(R_p + 1/\left(C_p d_0 C_{eq}\right)\right) + 1}$$

P_a / y *Pressure at the pump vs setting of the needle*

$$\text{E10)}\quad \frac{P_a(s)}{Y(s)} = -\frac{1}{C_{eq}} \frac{1}{s^2 \frac{V_0}{\beta} M_q + s\frac{V_0}{\beta}\left(R_p + 1/\left(C_p d_0 C_{eq}\right)\right) + 1}$$

E9) E10)





INJECTORS CONTROLLED BY VARIABLE NEEDLE POSITION SETTING: COMMENTS AND CONCLUSIONS.

The injectors controlled by variable needle position setting are more difficult to fabricate and - especially - to control. The first difficulty and cost is the installation of a proper needle position transducer with the related cables and protection devices.

The second difficulty is the necessity to fabricate and install a fast, powerful - but small and reliable - position control system. The max pushing force requested for a standard needle vary from 40 to 120 Newton, the controlled displacement shall be about 2 mm, the positioning response time requested is about 50 –100 millisecond in closed loop to permit a pressure response time of about 350 – 700 millisecond.

Open loop control

The open loop control is performed by positioning actuators that can be either mechanical or hydraulic devices. Both require a very precise positioning and a fast setting in case of replacement and a dimensional repeatability to reproduce standard working conditions.

When the position of the front of the needle is settable but fix the "feed forward" way to control the system is fundamental. Usually the "feed forward" function is realized by "on the field" setting i.e. positioning the needle in stated positions vs the nozzle and recording the working parameters, i.e. flow rate, pressure, viscosity in a specific matrix.

The software then performs a linear interpolation in the 3 or 4 dimension of the matrix to find the set point for the real working parameters: viscosity, flow, pressure, needle position. The needle is then moved in the setting position by the positioning control. If the system is fast enough it can compensate in "feed forward" also part of the pre-flow.

In not working conditions the injector is closed or set at the low pressure recirculation opening. The movement can clean the orifice.

With reference to the equation E9) Pi/y and to the related Bode diagram we can see that the pressure at the injector has a trough due to two poles combined with two zeros at the same characteristic frequency of the resin mass accumulated into the compressibility of the delivery line.

$$\omega = \sqrt{\frac{\beta}{V_0 M_q}} = 29 \text{ rad/s}$$

The dumping ratio of the poles (sum of the piping resistance and of the dissipation of the injector) is higher than the dumping of the zeros.

This behaviour means that the system can well self compensate the sudden blinding of the injectors when the spool opens and produce lower preflows.

The system itself is not sensitive to friction, being composed by a positioning closed loop that is dynamically stiff.

Build up of dirt in the nozzle during foaming is not compensated in open loop and this disturbance is full passing the control. The disturbance due to the opposite impinging jet is not affecting the position of the needle and depleted.

Closed loop control

The closing of the pressure loop is easier because everything is already prepared for the automation and the additional cost of the pressure control loop is negligible.

A pressure transducer can easily be installed close to the mixing head or close to the pump. The pressure control in closed loop for this case realizes an additional loop around and external to position control in closed loop. If the position control loop is almost five times faster than the pressure loop it acts as a strong stabilizer.

The stability of the system is guaranteed by this double loop that can perform at the best in terms of time response. Obviously the limitations is the cutting frequency of the mechanical actuator. This is the reason why hydraulic systems controlled by proportional valves are preferred.

The system is reacting also to the force and pressure disturbances and is not sensitive to the friction.

With reference to the equation E10) Pa/y and to the related Bode diagram we can see that the system can be stabilised with low frequency response also without the position control loop.

In conclusion

- this system is not easy to apply and costs more
- the preset of the injector position and repeatability is time costing
- the system requires a "feed forward" when it is not fast enough
- it is practically not adding cost when realised in pressure closed loop
- the stability is guaranteed and it's easy to set
- the force, friction and impingement disturbances are completely depleted
- the build up of dirt at the nozzle is not compensated.

GENERAL CONCLUSIONS

This Paper is part of the studies regularly performed at Cannon Afros for the development of new mixing systems and for the training of our young engineers. A deep study and schematization of the traditional injectors has been developed and summarized. Different injectors and their control, used in the PUR world by Cannon Afros and its competitors, have been compared to check the differences. The theory of the control systems and the Laplace transform have been applied to schematize and synthesize the behaviour of the different families of controlled injectors. Tests, experiences and fluidic simulation have been performed to confirm the trends. General considerations, suggestion and conclusions have been developed and presented in this paper.

This work allowed Cannon to find and apply a completely different way to mix PUR and to consider the influence of injectors. The theory has been applied to the new Cannon JL, a Jet-less mix head presented with a separate Paper in this Conference. The tests and the use of the JL mix head confirmed that better mixing efficiency and foam performances are reached.

Let me thank the Engineering and the R&D Departments' staff, as well as the Cannon Group's Chairman for the opportunity given to develop and consolidate this work.

Thank you for your attention!

Biographies

Maurizio Corti, born 1954, is the Technical Director of Afros SpA, the Cannon Group's Company manufacturing Polyurethane metering and mixing equipment. Maurizio graduated in Mechanical Engineering from the Politecnico di Milano University in 1980, with a work on the theory of control systems, which constitutes the basis of this paper.

Mirko Colombo, born 1982, graduated in Mechanical Engineering at the Politecnico di Milano University in 2005, and is currently studying to achieve the specialization in Mechatronics. He's undergoing a stage in the Engineering Office of Afros SpA. Mirko conducted the schematization of the system, linearized the equations, applied to them the Laplace transform, analyzed the configurations and the frequency response.