Fill valve competitive design

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Abstract

The paper deals with the development (concept, design, optimisation and manufacture tooling) related to a fill valve for domestic toilets. Such item is a product of extremely wide consumption and must cope a very strong internal and international competition. Price, real and perceived quality, and compatibility with other contiguous components are weapons for the commercial fight. The fill valve is operated by a back pressure amplifying device with innovative elements. The innovation has been lately chosen by Western industry to cope the extremely low cost of Eastern manufacturers (mainly China and India based). Of course only low cost innovation can be proposed, and the cost of tooling and manufacturing has been considered with attention.

The paper deals in detail with the mechanical development of the item, while giving a reference commercial frame.

Keywords: Fill valve, Innovation, Competitive design.

1. FOREWORD

A domestic toilet fill valve is a device that manages automatically the filling of a 10-15 litres water tank connected to a WC, dedicated to clean it after every use.

This device is typically subject to troubles like noise during tank filling and during valve closing, leaking, blocked device, limestone deposition.

The valve functioning generally relies on a float that manages its closing phase.

The float position should be adjustable to choose the amount of water for tank filling.

The fill valve device should be absolutely reliable, very cheap and as small as possible, due to the actual tendency to use thin tanks to be inserted in houses' walls.

This kind of device is in the "mature phase" in its commercial lifetime, so a lot of solutions are yet been explored, and innovation is very difficult. The market is also very diffident to new solutions so, every innovative device should not be too much apparently different, while at the same time it should be well proved to be 100% reliable. This implies also a very hard war on prices, so there is very little money budget to be spent in innovation. It means that consumer is not willing to pay too much premium price for an innovative device.

Nowadays emerging countries (China, India) are strongly competitive on prices, so it is mandatory for western companies to be competitive with new devices, being on the edge with creativity and innovation.

This outline of the situation explains how any product improvement or innovation must be managed through reliable and "low cost" innovation

2. FILL VALVE CLOSING PHAENOMENA

To be clear in explaining our innovative design, it is helpful to describe how fill valves mostly function.

There are mainly two categories, with "piston" principle and with "back pressure" principle. The first category functioning is explained in *fig.1*. In the upper part of figure a functional scheme of the "piston" valve is depicted while in the lower part there is a graph showing forces vs. time. (This figure scheme will be maintained for other schemes).

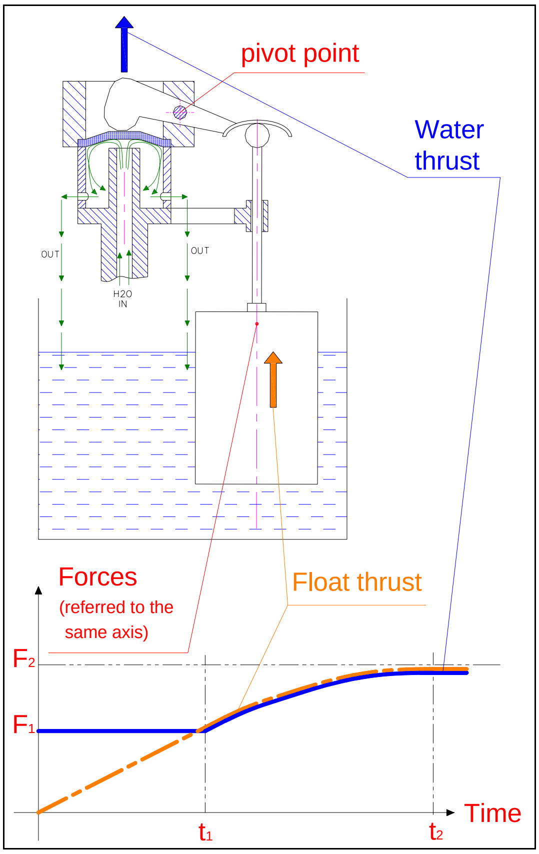

Fig. 1. “Piston” Valve

Float (*fig. 1*) is pushed upwards by water level and it operates (directly or through a rocker arm) a plastic cap or a rubber membrane to close the water inlet.

Depicted graphs are qualitative; in all graphs forces have to be considered as referred to a common application point, to be properly compared.

Looking at the lower graph it is possible to see water inlet force on rubber membrane, due to water pressure, with open valve (F_1). Water flows in the tank and float thrust increases until it reaches F_1, when float begins to move upwards pushing the membrane to close. In the meanwhile the reduced gap for water causes the pressure to increase, as a consequence the force applied to the membrane by the float must increase too (further rise of the water level). Therefore the closing process speed slows down during execution resulting in noisy and long lasting shutting phase. Nevertheless, with a proper design, this kind of valve proved to be very useful, reliable and cheap and it is the most diffused especially in third world countries or in countries with high limestone content in water.

To overcame such limitations many solutions are applied in commercial production, one of which is outlined in the following. It is usually defined the “back pressure” mechanism.

It is similar to the previous one, with an additional water chamber inserted between the rocker arm and the rubber membrane. A small calibrated hole is performed in the rubber membrane and another small hole is placed on the top of the chamber; this second hole is to be closed by the rocker arm (*fig. 2*).

For explanation issues, let’s refer to inlet pressure as “P_i” and chamber pressure as “P_c”.

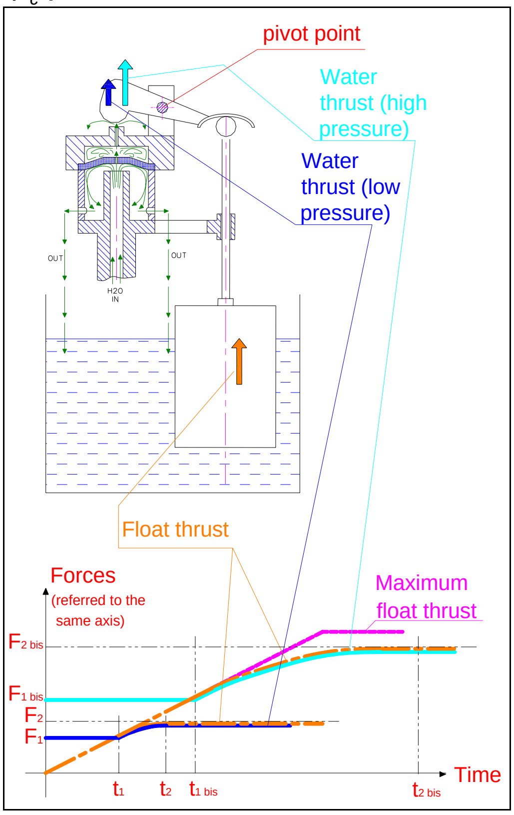

Fig. 2. “Back pressure” valve

Inlet pressure operates on an area “A_4”, while *Pc* pressure operates on a wider area “A_3” (*fig.4*). When valve is open (as depicted in *fig.2*, top), a flow through hole in rubber membrane towards the hole on the top of chamber and out, causes a slight drop in pressure from inlet to chamber so that:

$$P_i \cdot A_4 > P_c \cdot A_3 \quad (1)$$

Therefore membrane is locked in “open” position. Conversely, when float pushes rocker to close the top hole, suddenly water flow ceases and chamber pressure raises to *Pi* inverting the sign of the previous equation (1):

$$P_i \cdot A_4 < P_i \cdot A_3 \quad (2)$$

simply because $A_4 < A_3$ (3)

The closing movement is fast and, once valve is closed, it keeps itself closed regardless of inlet pressure variations as it can be known by (2).

All the concerns related with closing phase in "piston" valves disappear due to the small movement required to close the pilot hole on the top of the water chamber and the size of that hole itself (blue line in *fig.2*). It can be understood, that small exit hole size implies small (absolute) force variation during closing movement.

In conventional design, this applies very well with regard to domestic pipeline pressures in Europe (1-5 bar), but there are countries with much higher pipeline pressure; it implies a much higher absolute differential between flowing and static pressure (*fig.2* cyan line, F_1bis-F_2bis) that take us back to problems related to "piston" valve.

In a test campaign dedicated to this valve also instability and damped vibrations problems were experienced in such "high" pressure field.

After commercial and ROI considerations, it was decided to design a new type of back pressure valve that could cope with in-line high pressure problems.

3. EXPERIMENTAL CAMPAIGN

An extensive experimental campaign was performed, using a special device designed and built in-house.

We bought, in commercial stores, tens of different valves (with different working principles) and we processed them under a predefined series of conditions, to verify their functioning and discover where and why eventually they fault.

It could be too much distracting to argue about that campaign here, but it is in scheduling to publish some data about that in the future.

A dedicated test set up was designed and manufactured in order to allow executing tests in accordance with AFNOR NF EN 14124 and NF 076 which are considered as "standard". The market calls for products reporting a badge that testify their behaviour under NF 076.

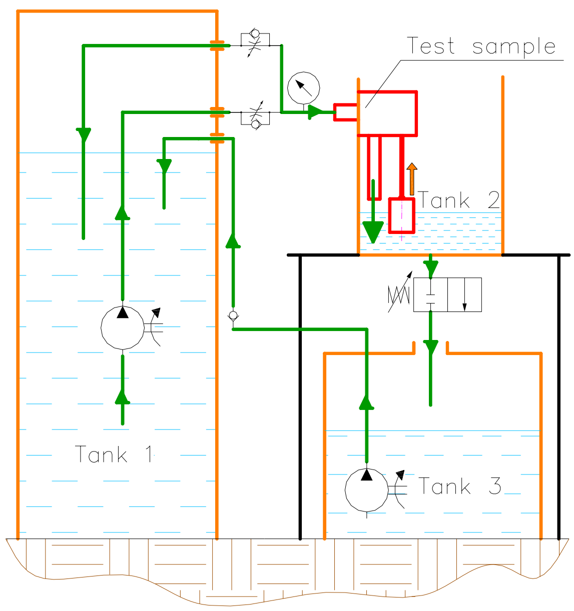

Fig. 3. Test device

The specifications requested to a fill valve by foretold rules are:

- Dynamic in-line pressure sustained: 0,5-10 bar.
- Recommended for correct functioning: 1-5 bar
- Flow rate at 0,5 bar: 6 litres in less then 180 s and 9 litres in less than 240 s
- Valve must open for a float descent of 65mm
- Successive closure must be within +/-5mm of precedent level
- Water hammer : 2 bar max (e.g.: 5 bar static to 7max during closure)
- Pressure resistance: no visible leaking or deformations at 16 bar (for 5 minutes)
- Static pressure test: closure at 0,5 bar then (valve always closed) go to 3 bar for 5 mins then go to 10 bars for other five mins (control leakage)
- Durability: 25000 closure cycles at 1,5 bar + 25000 closure cycles at 8,5 bar (NF: 200.000+200.000)
- "Explosion resistance": 1000 cycles with square pressure waves from 10 to 30 bars with valve closed.

All the purchased valves were tested with reference to all above points, exception made for the last two ones. Furthermore all valves experienced a quick on-off sequence at 16 bars inline.

After this long experimental campaign we discovered some different problems at medium high pressures (8-10 bars) :

- Long closure time for piston valves with noise; in some cases missed closure for scarce float dimensions
- Beginning of problems for back pressure valves with longer closure times.
- In some cases, with back pressure valves, vibrations phenomena at the closure (e.g.: series of rapid opening closing of the membrane until subsequent leaking gives more thrust to the float)
- At higher pressures (15 bar) leaking from some valve body.

Fig. 4. A competitor's valve in test

4. INNOVATION

After a deep analysis of all experimental data, some conclusions were drawn and some main faults of competitors' valves were enlightened:

- Back pressure valves are quieter and smoother in operations
- They can withstand very high pressure once closed but can have troubles during closure, beginning at 8 bars ca.
- They are conceived for smaller pressure operations so they have longer closure time at higher pressures
- It may be sometime useful to increase float dimensions in problematic valves, but it may have negative impact on operation dynamics as it causes an early start of shutting phase, going to operate on top chamber water jet without the force needed to cope with it, so it is necessary to wait some time in this position until water level raises and operates float correctly.

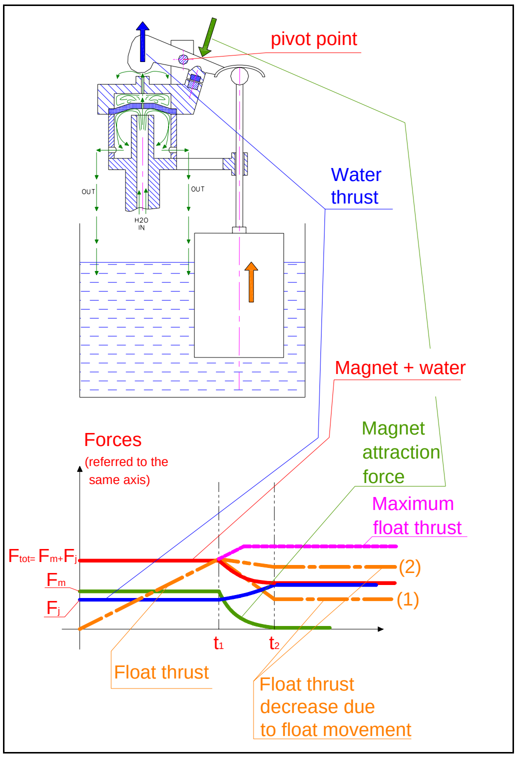

Fig. 5. "Back pressure + Magnet" mechanism

This last consideration was the driving thought when it was decided to conceive and design a new back pressure valve.

The goal was to invent some device to make the valve use correctly (and all at the same time) the float volume.

In our mind this should solve all problems related with higher pressure closure and early float movement.

It was decided to use a magnet in the rocker arm coupled with a ferromagnetic material in the valve body to act as a "force switch". In fact, this solution, if correctly designed, can keep the float and rocker arm still, until float thrust reaches and passes magnet attraction force.

Then float moves, magnet moves away from ferromagnetic material, their attraction falls down, so float can express all his thrust (free from magnet resistance) to close piloting water jet (*fig.5*).

In *fig. 5* it is possible to study how the sequence can happen. It is important to remember that the graph here is qualitative.

Graph in *fig. 5* represents forces vs. time. In orange dotted line float force is depicted: it increases as water level grows, theoretical limit being his volume (magenta continuous line). In blue line water jet force is depicted (*Fj*). It is constant until rocker arm act on it (t_1), and then it increases to the static pressure force (t_2).

Magnet attraction force (*Fm*) is depicted in green: it is constant until movement starts (t_1), then it decreases quickly (to t_2) during arm movement because of growing distance from magnet to iron.

It is important, now, to consider the opposing forces: on one side magnet + water jet, on the other float thrust.

If we compare magnet + water jet force (red line, *Ftot*) with float thrust it is possible to see that, until the latter overcome the former, there's no movement then, suddenly, when float force exceeds, arm moves and total resistance falls down (due to magnet force falling).

This results in a growing exceeding force (magnet force is falling down to zero) that implies a brief and silent closure.

Rapid upwards float movement implies a rapid decrease in float thrust too because it partly emerges from water (*fig. 5* orange dotted lines between t_1 and t_2); depending on float form and dimension it can even result in instability of movement, if float force (*fig.5*-(2)) falls beneath total magnet + water force (red line).

So it is comprehensible how important having a correct mathematical model is to foresee valve behaviour.

5. VALVE MATHEMATICAL MODEL

In a first time a conceptual design of the new valve was sketched up to spot the general lay out, in order to fix some parameters range for the most important dimensions.

The general lay out was also the base on which it was possible to create the mathematical model for the valve behaviour during operations.

During this phase it was also possible to choose a magnet on the basis of this rough design.

In *fig. 6*, a summary of the most important parameters considered in the build up of the model is depicted. Some parameters are strictly linked to others.

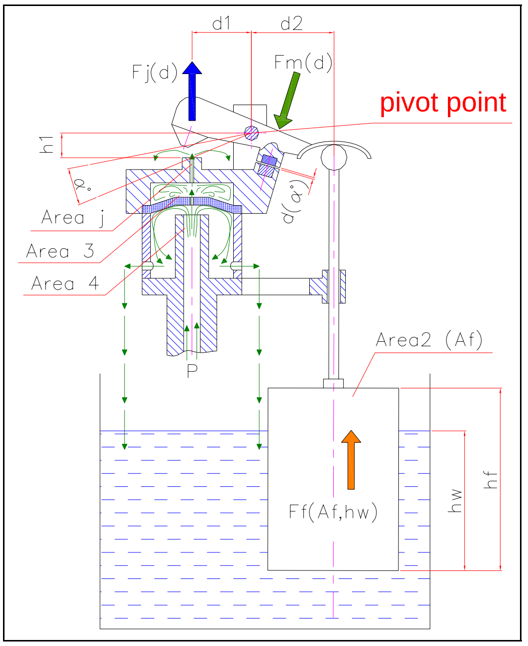

Fig. 6. Model parameters

In order to build a correct valve model (to predict his behaviour), it is mandatory to start with correct components' models.

Some physical phenomena have not linear dependence with dimensions and are often heavily influenced by environment, so it's necessary to have experimental data to fit a model.

It was therefore necessary to carry out a data measurement campaign on the magnet characteristics (related to a particular ferromagnetic material) to obtain a characteristic curve "force vs. distance", to be inserted in the model

This was the most essential parameter of the model because it would be very dangerous to rely simply on a prediction.

Moreover, some versions of preliminary design prefigured some plastic inserts between magnet and iron, then experimental data were essential.

Using a small traction machine for springs, equipped with a load cell we acquired data from a batch of magnets, sweeping through fixed distances from iron (*fig. 7* shows some results).

Test data were interpolated by way of a polynomial function (first part of stroke) followed by an exponential one.

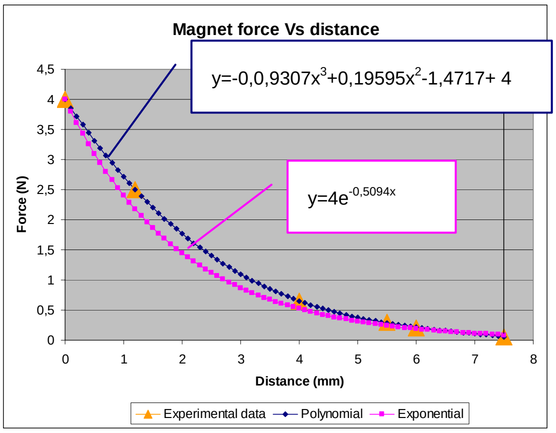

Fig. 7. Magnet acquisition and models

Skipping the entire model's maths for space reasons, we represent briefly a couple of results graphs.

What the reader can see plotted in figure 8 is what happens in the gap of time between start and end of closing movement (formerly called t_1 and t_2). This graph is referred to the final configuration chosen for production.

For comparison purposes all the forces involved are plotted as torques referred to the pivot point of the rocker arm.

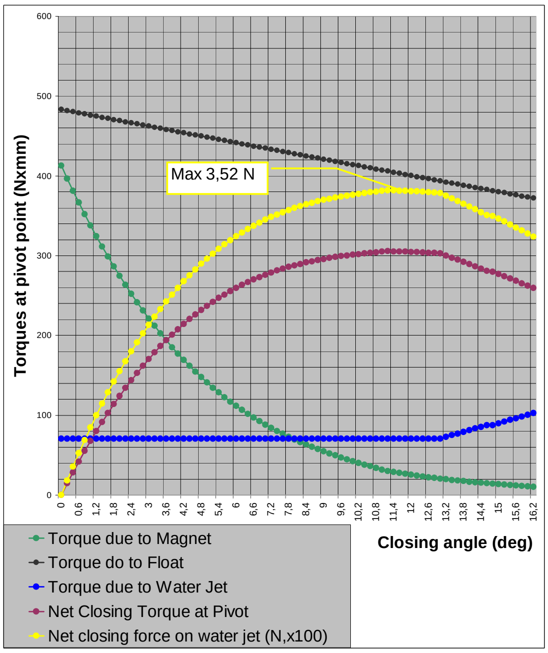

Fig. 8. Transition time, production configuration

Referring to *fig. 8*: in green the torque due to magnet, in blue the torque related to chamber water jet, in black torque due to float thrust. It is interesting to observe the curve shape strict resemblance with what predicted in *fig. 5*. The purple curve is the net closing torque applied to the arm, so the net resulting closing force has a maximum of 3,52N with a remaining of 3N after closure

It is also interesting to look at a different parameters set, resulting in a non closing valve. The following *fig. 9* shows behaviour of the same valve as *fig.8* except for the chamber water jet diameter changed from 1 to1,2 mm and for the float height passing from 70 to 50 mm.

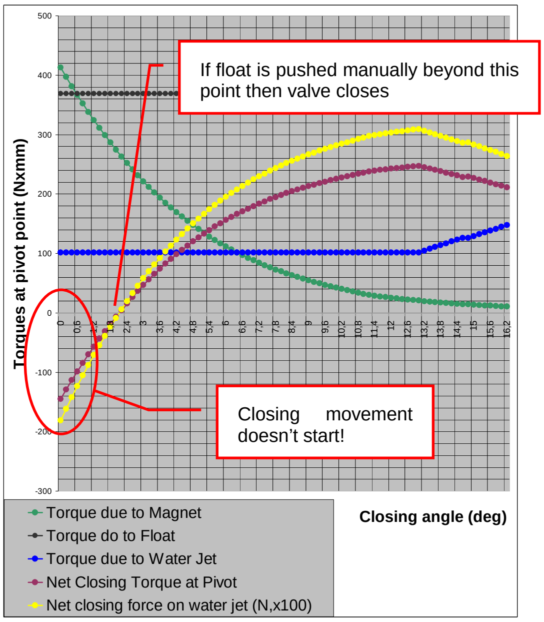

Fig. 9. Transition time, discarded configuration

Notice, in blue, the increased water jet torque (both dynamic and static) and the decreased float torque (black line). It's immediately visible how net closing torque is negative at t_1 (corresponding to closing angle 0°, start of the movement). This means that float volume isn't sufficient to overcome other forces (magnet + water jet) and so movement doesn't begin even if water level passes over float. It is also interesting to se that if float is slightly pushed upwards, more than 2° of movement, float can continue on his own to move.

We must consider that production configuration has not been frozen quickly at this stage because design issues involved changes that needed to be reviewed and corrected some times with model in a so called "design-loop".

6. DESIGN EVOLUTION

In this paragraph a brief survey on valve design evolution will be presented. It was chosen to show only a brief sample of design variants due to the great mass of them. Besides perfect functionality under specifications, design goals were

- Small dimensions: complete valve should fit in smallest commercial in-wall tanks, with some manoeuvre space for operator's hands.
- Modularity: market asks for some different version depending on application, so, to be competitive on price it was necessary to develop an entire valve family on a common product base. Market also asks, depending on countries, for brass or plastic fittings to the inlet.
- Tooling economy: moulds number should be as low as possible. This implies also lower assembly costs if there are less assembly operations.
- Maximum number of common parts to spread tooling costs over biggest productions.

So, starting from common core components we developed 4 version: a)Lateral fit with screwed-in brass insert *3/8G* or *1/2G*, b)Lateral fit with all plastic *3/8G* terminal c)Lateral *3/8G* brass fit over-moulded with plastic d)Bottom fitting with height regulation.

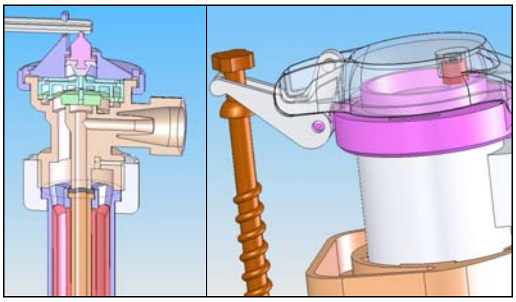

Fig. 10. Rocker arm design studies, at right two pieces rocker arm+ cam in valve cap.

It was really very hard to simultaneously develop all this versions together. We travelled through a high number of intermediate design steps (*fig.10-15*), being a correct design the key to project success. Each design step was also built using RP techniques or machining in plastic or aluminium, to be evaluated on test bench.

Even if it could seem to be a less important aspect in this case study, it was discovered that buyers give high importance to valve aesthetic impact, so an ID review was also necessary at each design step.

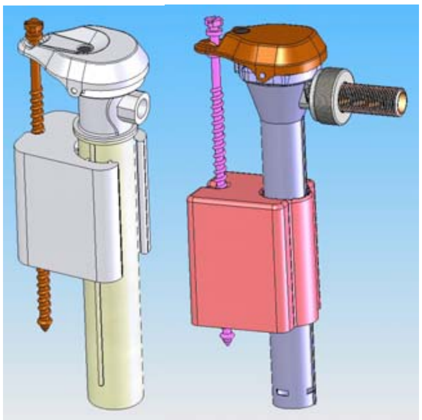

Fig. 11. Intermediate shape changes

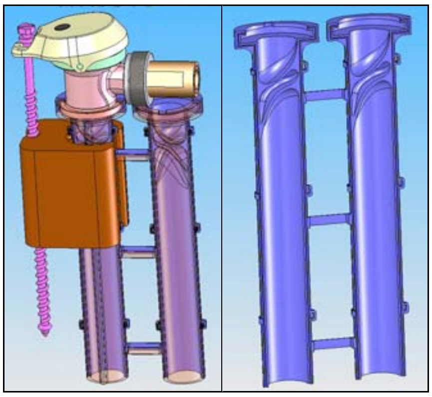

Fig. 12. Study of a high turbulence double-shell outlet tube

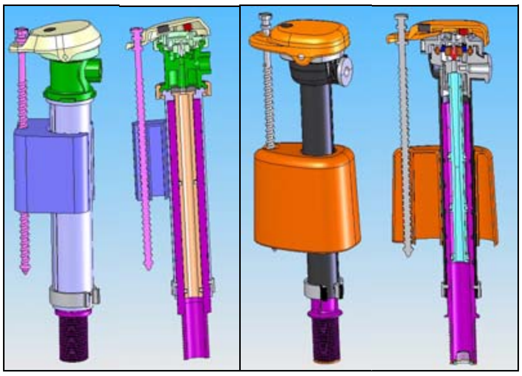

Fig. 13. Evolution of bottom inlet version

It would be very ineffective trying to explain in a short paper all the design evolution history, but authors will be very glad to explain, if asked.

In *fig.14-15* reader can evaluate final design solution. Key components in all design development were the main valve body (*fig.14*, black arrow): and water chamber cap (*fig.16*).

Great effort was dedicated to their shape, which was optimized with an iteration using FEM tecniques and mold flow analysis, because these components must withstand

30 bars being moulded in POM (acetal copolymer).

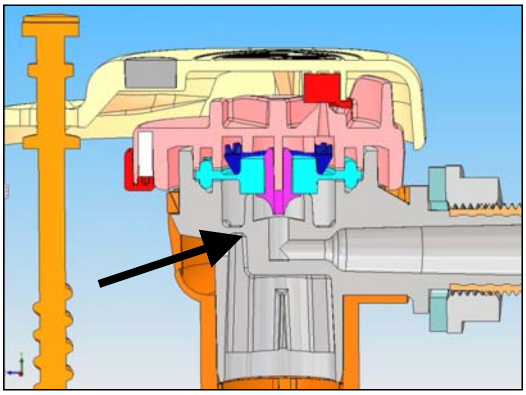

Fig. 14. valve section, final version

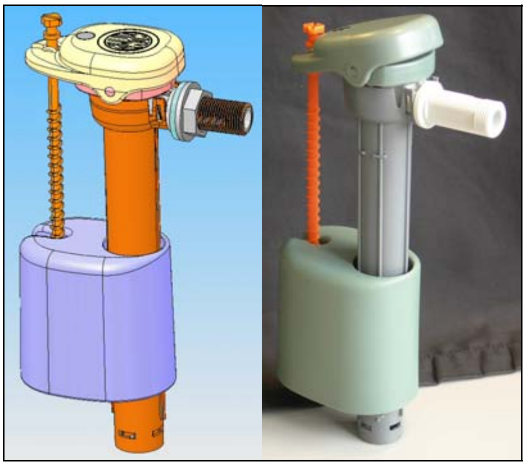

Fig. 15. Valve assembly, pre-series protoype

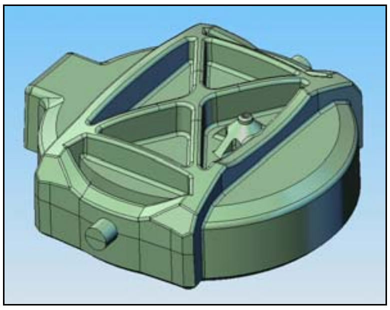

Fig. 16. Top water chamber cap final version, after FEM optimization

7. TOOLING OPTIMIZATION

A great care was devoted to the design of the valve main body. Four possible varieties of it were developed, having in common the same basic structure, and differing for few surfaces mainly. The purpose was to design a moulding tool fit to allocate interchangeable parts, so to get four different valve shapes substituting proper inserts in the same basic mould structure. The goal was achieved. It was required to perform a deep study of the component morphology due to trade-off between water flow considerations, mould flow consideration, shrinkage after moulding, mould insert mechanical, and, of course, correct functionality

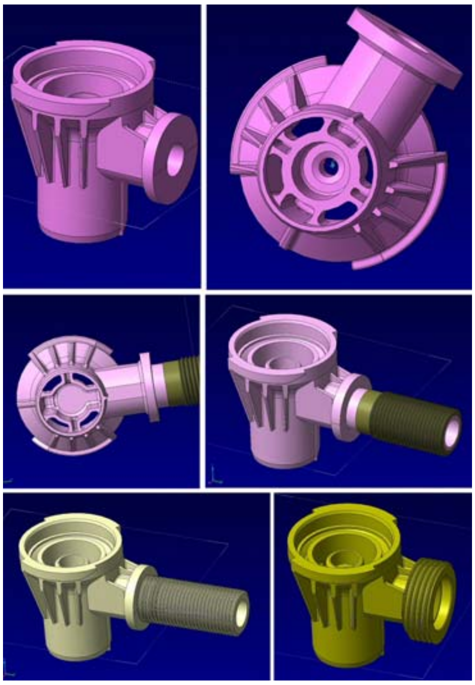

Fig. 17. Valve body configurations

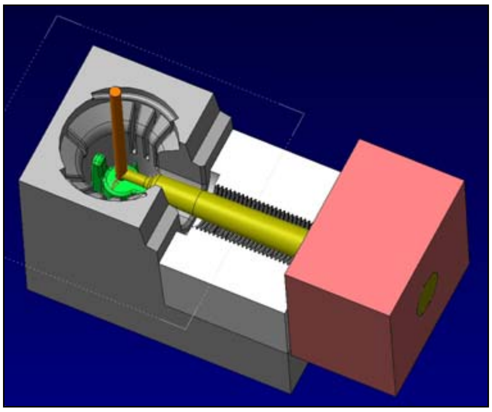

Fig. 18. Mould inserts study

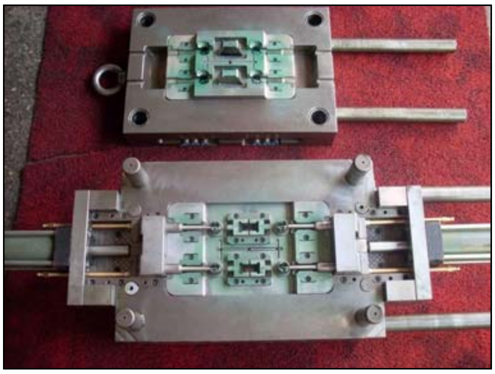

Fig. 19. Mould with interchangeable inserts

Then the most expensive part of the mould, with complicated geometry and need to use

EDM machines with relative tooling costs, was done once. The resulting tooling, even if more complicated, was much cheaper than a set of four different simple moulds.

During the tooling manufacturing period, a set of valves was needed to speed up testing phase. For quality assurance purposes, a 100% control on production during tooling transition phases guarantees trouble free products (e.g.: when production starts or when a different variant of valve body is put in production).

A cheap test set up (fig 20, 21) was designed to test manually all valves. This device operates on the semi-assembled valve (without outlet tube and float) and simulates the float thrust with a weight and a rocker arm. Handling is limited to loading, pipe connecting, pressure monitoring and unloading operations. A really low cost device allowed executing more than 350-400 test/man x hour.

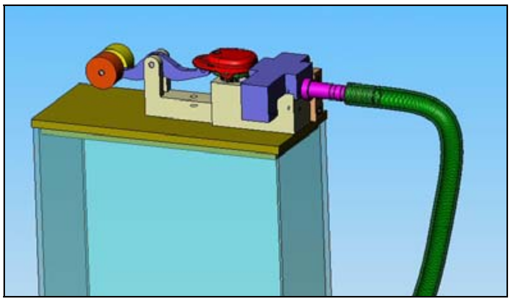

Fig. 20. Test machine

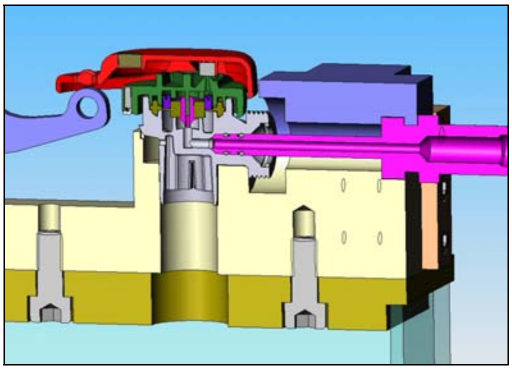

Fig. 21. Test machine (section)

8. CONCLUSIONS

In this paper we showed how a proper design approach to an industrial problem can lead to innovation (magnet use in fill valves) with explanation, through a mathematical model, on its functioning principle. Proper calculation and design applied to this innovative (for the field) application can lead to a general dimensional contraction of a valve, and a more efficient use of the float volume.

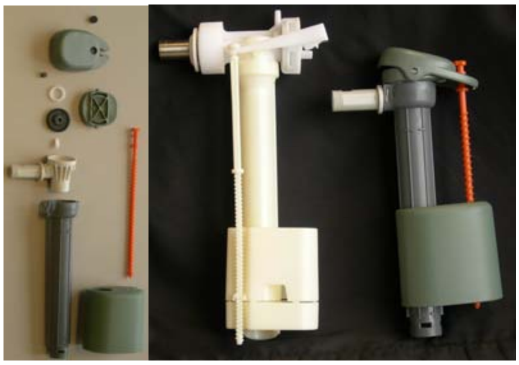

Fig. 22. exploded view and comparison with a competitor's sample

It was also shown how a design integration from the kick off of a new project can result in a cheaper tooling cost thanks to variants implementation from the beginning of the project itself. (*fig.22*)

Further development may deal with problems due to possible dirty or limestone rich water, as experienced during the "make & test" phase of the project. To solve these problems we think that a piston valve with a proper magnet application should be appropriate.

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