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ABSTRACT.

The Gas Introduction Module (GIM) is the basic system used in JET to provide the vacuum vessel with the amount of gas necessary for a successful plasma discharge. The Plasma Density Feedback (PDF) system controls the GIM Piezo Electric Valve allowing the desired amount of gas flowing in the vacuum vessel. The unavailability of a flow measurement is the main reason for the development of an accurate flow model, able to predict and calculate the number of particles flowing within an acceptable error margin. This paper describes a GIM model that uses the control signal of the piezo-electric valve to compute the pressure evolution inside the GIM reservoir and, using the pressure estimation, obtains the particles flow considering also the dynamic heat exchange effect between the gas and the structure of the GIM.

1. THE GAS INTRODUCTION MODULE

The Gas Introduction Module (GIM) is the main actuator of the Plasma Density Feedback (PDF) system at JET [1]. Its aim is to control the number of particles flowing into the vessel by regulating the aperture of a piezo electric valve according to the control signal provided by the PDF. The reliability of the GIM and the availability of accurate flow estimations are the key features of a robust Plasma Density Control System. Figure 1 shows the schematic of a GIM highlighting its crucial components: the 1.5 litre calibrated reservoir, the piezo electric valve, the V2 valve and the pressure gauges. The local reservoir can be isolated from the supply lines by closing the valve V2 in the GIM, which is the normal operating mode during pulses. Moreover, when large amounts of gas are required, it is possible to operate with the valve V2 open. The number of particles flowing into the vacuum vessel is the crucial information that has to be provided to the control system. An accurate model of the GIM, accounting for the operating mode, considering dynamic effects that take place during the gas flow and providing a precise particle flow estimation is of key importance for the development of both a real time Plasma Density Control system and a post-pulse analysis tool. The model used at present to describe the flow evolution uses static non-linear waveforms that had been obtained from a wide class of experiments. These experiments, anyway, did not focus on dynamic effects taking place during the gas flow and on non-linear problems due to the piezo-electric valve that in fact influence the flow evolution. The flow process is only partially described by the obtained waveforms consequently affecting the estimation with a non-negligible error. The aim of this paper is to provide a model that describes the dynamic non-linear processes, produces a better gas flow estimation and computes, as secondary output, the gas temperature evolution.

2. DYNAMIC NON LINEAR MODEL OF THE GIM

The dynamic model described in this paper aims to compute the flow process using the control signal of the piezo electric valve and the initial reservoir pressure as inputs and producing the gas flow evolution as output. The model has been decomposed into two simpler models: one describing the pressure evolution in the GIM reservoir according to the piezo-electric control signal, the other computing the flow evolution using the previous computed pressure signal and considering dynamic heat exchange effects. A schematic describing the GIM model is shown in Figure 2. The main difficulty of the Opening to Pressure Model (OPM described in depth in Section 2.1) is to properly describe the non-linearity between the control signal of the piezo-valve and the obtained valve aperture. A 20% hysteresis on the valve behaviour has been observed during calibration experiments that had been done in the past. The pressure estimation obtained by the OPM is used by the Pressure to Flow Model (PFM see Section 2.2) by computing the gas flow as the derivative of the pressure signal considering also the influence of the gas temperature evolution. The effect of the gas temperature can be appreciated from Figure 3 that shows an example of the valve opening signal and the corresponding pressure evolution measured inside the reservoir. Computing the particle flow simply as the derivative of the pressure signal, ignoring the heat exchange, can lead to inaccurate results; the pressure is changing even when the piezo-electric valve has been closed (see phase between 59 second and 62 second in Figure 3). In order to solve this problem, a thermal model of the GIM has been developed. After the valve closure the pressure has been identified from experiments to evolve as a first order system with a defined time constant where the only unknown parameter is the amplitude of the exponential function. The idea is that the pressure evolves according to a formula like $P(t) = P_{clos} + K(T_{amb} - T_{gas})(1 - e^{-1/\tau})$ where P_{clos} is the pressure at the time the valve is closed, K is a GIM dependent gain and τ is the time constant of the heat exchange process. Knowing the pressure, the starting gas temperature (assumed to be equal to the environmental temperature) and the control signal of the piezo-valve the dynamic model computes, in each instant, both the pressure evolution in the reservoir, the flow estimation and the internal gas temperature.

2.1 THE OPENING TO PRESSURE MODEL (OPM)

The OPM model describes the relation existing between the control signal of the piezo-valve and the pressure evolution, taking into consideration both the non-linearity between the drive signal of the piezo-valve $C(t)$ and the achieved valve aperture $S(t)$, and the thermal evolution of the flowing gas. The valve non-linearity has been modelled as the sequence of two blocks. The first block describes the aperture phase of the valve, paying attention to ‘sticking’ on the valve seat that has been observed during experiments. Basically it has been observed that almost half of the full control signal is necessary to first move the valve from its starting position. Two different waveforms have been used to describe this process; the first is only used during the first detachment phase and considers the valve still closed until half of the full control signal is used. The second waveform describes an almost linear relation between the valve control signal and the valve aperture. The second part models the hysteresis characteristic of the piezo-electric valve as a hysteresis relay. Anyway it is worth noticing that is impossible to know exactly the valve aperture because of high-non-linear and not predictable phenomena that cause the valve to behave slightly different from experiment to experiment. Using the estimated value of the valve aperture $S(t)$ and knowing the gas speed $v(t)$ it is possible to compute a rough estimation of the particles flow using the formula

$\psi(t) = v(t) \cdot S(t)$ where a questionable assumption of constant gas density has been done. The gas speed $v(t)$ has been computed modifying the well known Bernoulli theorem $v(t) = \sqrt{2/\rho(P(t) - P_{vessel})}$ and assuming once again the density ρ constant during the flow. Even if the assumption of constant density is questionable, the results obtained are within the desired error margin. This can be explained considering that the amount of gas that is usually injected in the Torus vessel is very small compared to the one available in the reservoir. Consequently the pressure (and density) decreases only by a small amount. Using the $\Psi(t)$ estimation and the thermal model that will be described in Section 2.2, this system computes the pressure evolution in the reservoir. This is achieved by integrating the flow signal $\Psi(t)$ to obtain the number of particles flowing. By subtracting this estimation to the initial number of particles contained in the reservoir the number of particles left is obtained. From this information it is possible to compute the pressure in the reservoir within an acceptable error margin. The formula implemented to compute the pressure evolution in the reservoir can be described by $P(t) = P_{initial} + f(T(t)) - R\int\Psi(t)dt$ where $P_{initial}$ is the starting pressure in the reservoir, $f(T(t))$ describes the pressure dependence on the gas temperature (see Section 2.2) and R is a calibrating constant. An example of the pressure estimation obtained with this model compared with the real pressure signals is shown in Figure 4. The small discrepancy observed in the last part of the figure is due to the difficulties on providing a completely reliable model of the valve aperture behaviour and on the impossibility to predict completely the behaviour of the valve aperture as already told. Problems regarding this unreliability are described in depth in Piccolo [2] (page 37).

2.2 THE PRESSURE TO FLOW MODEL (PFM)

The output $P(t)$ provided by the OPM is used as input for the second model that produces the flow estimation as derivative of a non-linear function of the pressure signal. The main assumption that has been done to derive this formula is that the process can be split into two different phases: the first phase considers the pressure evolution as an adiabatic expansion while the second part describes the thermal exchange as an isobaric heat exchange. The adiabatic expansion choice has been done to avoid problems due to particles flow that are not considered in the basic thermo-dynamic formulae; the pressure decrease has so described as a volume expansion instead of a particle flow. The formulae used to derive the non-linear model are:

$$P(t)V = N(t)K_b T(t) \qquad (1) \qquad T(t)P(t)^{\frac{1-\gamma}{\gamma}} = const \qquad (2)$$

where K_b is the Boltzmann constant, $N(t)$ is the number of particles contained in the reservoir, V is the reservoir volume, $P(t)$ is the pressure, $T(t)$ is the gas temperature and γ is the ratio of the c_p and c_v specific heat constants. Deriving both equation (1) and (2) and substituting the temperature derivative of equation (1) with the derivative term obtained from (2) the following formula is obtained:

$$\frac{dP(t)}{dt}V = \frac{dN(t)}{dt}K_b T(t) - N(t)K_b\left(\frac{1-\gamma}{\gamma}\frac{dP(t)}{dt}\frac{T(t)}{P(t)}\right) \qquad (3)$$

Rearranging this formula to isolate the particle derivative and eliminating the V term the following equation is obtained:

$$\Psi(t) = \frac{dN(t)}{dt} = \frac{1}{\gamma}\frac{dP(t)}{dt}\frac{N(t)}{P(t)} \tag{4}$$

This formula describes the flow evolution using the pressure signal but it is not complete. According to equation (4) when the flow is zero (valve closed) also the pressure derivative should be zero but this does not occur as shown in Figure 3 due to thermal exchange of the gas with the GIM structure. As mentioned before the temperature evolution is that of a first order system and it can be added to equation 4 to give the final model:

$$\frac{dP(t)}{dt} = \frac{N(t)K_b}{V\tau_{th}}\left(T_{amb} - T(t)\right) + \gamma\frac{P(t)}{N(t)}\frac{dN(t)}{dt} \tag{5}$$

The term T_{amb} is the temperature of the reservoir which is assumed constant, t_{th} is the time constant of the heat exchange process. In order to obtain an estimation of the accuracy of this model, the number of particles flowed, computed as integral of the flow signal, has been compared with the Post Pulse File (PPF) signal GASM. GASM is a post pulse analysis of the GIM behaviour and uses static non-linear equation to reconstruct the pressure evolution from the valve aperture signal not considering the thermal influence. The final value of the pressure signal is already known to GASM that describes the pressure evolution only during the aperture phase of the valve. Once the valve has been closed the pressure signal is kept constant and equal to the final value. In this way the heat exchange process is negated and the gas flow rate easily computed. Unlike the GASM the model described in this paper is a real time model. The value of the final pressure is not known and all the information has to be computed in real time using only the valve aperture signal and a much more complicated model. The results obtained with the real time model, shown in Figure 5, demonstrate that good estimations are obtained.

3. CONCLUSION

The model described in this article can be used for different purposes in JET: it can be used as a post pulse analysis tool, as a pre pulse analysis tool and as a real time system. As post pulse tool it can be used to improve the GASM estimations or as a cross validation system. As a pre pulse tool it can simplify the work of the Session Leaders operating the tokamak, allowing them to choose in advance the particles flow that is going to feed the plasma. At the present the Session Leader does not know the exact gas flow because he only has an approximated idea given by the percentage of the maximum flow. The idea is that, using a predefined aperture waveform, the Session Leader can compute the number of particles feeding the plasma during the different phases of the discharge. Finally as a real time system it can be used to improve the GIM behaviour and to simplify the design of a reliable Plasma Density Control system. This last part has been treated in depth in Piccolo [2]. Finally a linearised version of the model can be used to design a GIM control system that accepts the flow waveform as input and reproduces the flow as output. This will have as second effect the benefit of simplify the user interface facility in the designing phase of a JET pulse.

ACKNOWLEDGEMENTS

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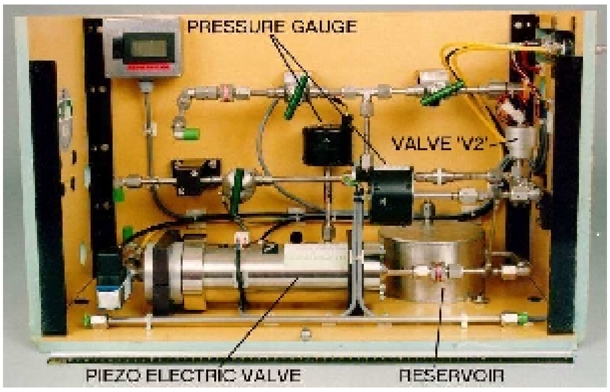

Figure 1: General schematic of a GIM. [3]

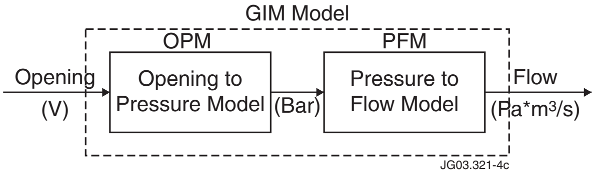

Figure 2: Schematic of the GIM model described in this article.

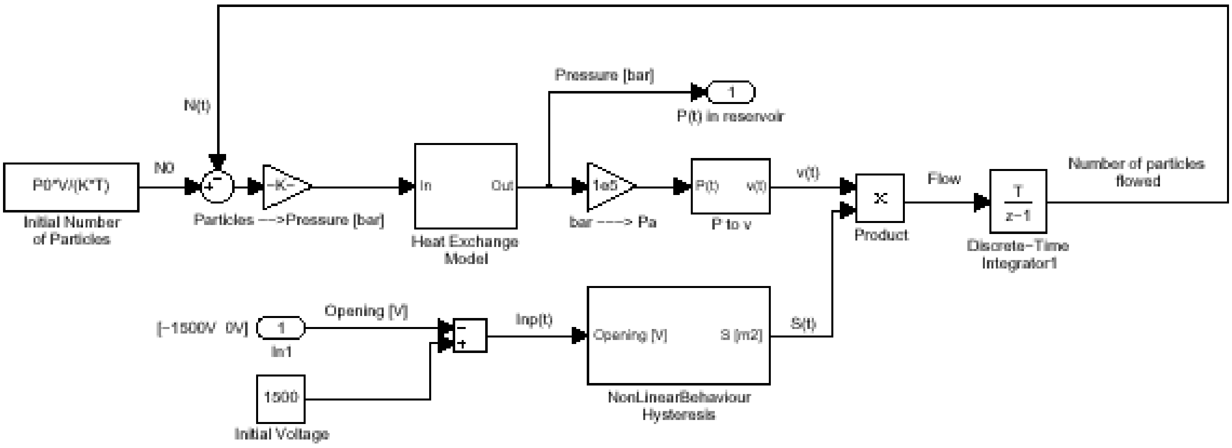

Figure 3: Example of the pressure evolution measured in the GIM reservoir and of the piezo valve command signal. Notice the pressure exponential evolution after the valve closure.

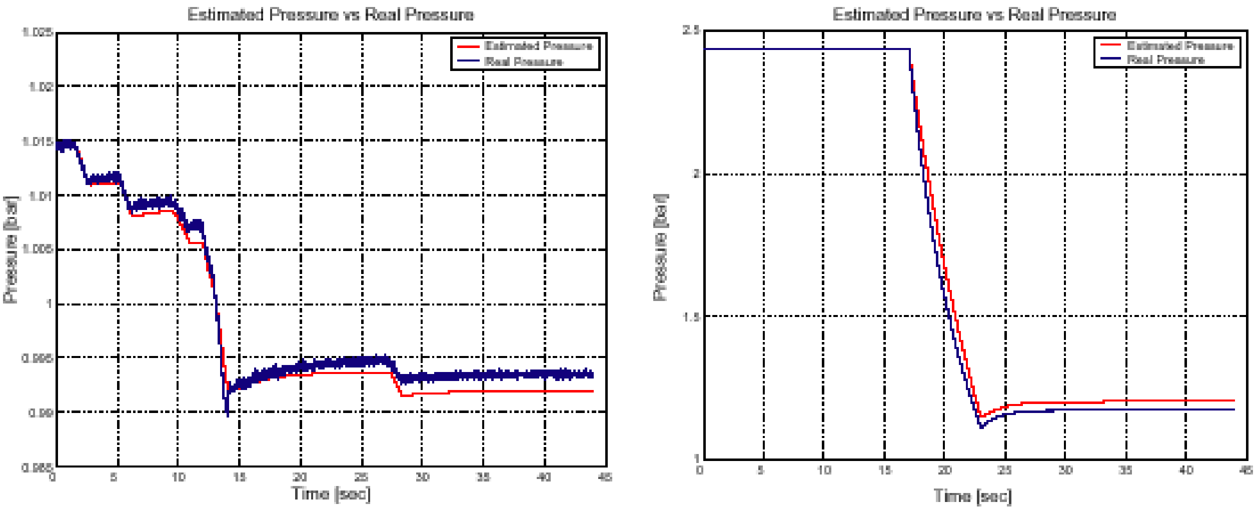

Figure 4: Example of the pressure estimation obtained with model OPM compared with the signal measured in the reservoir by the Pressure Gauge.

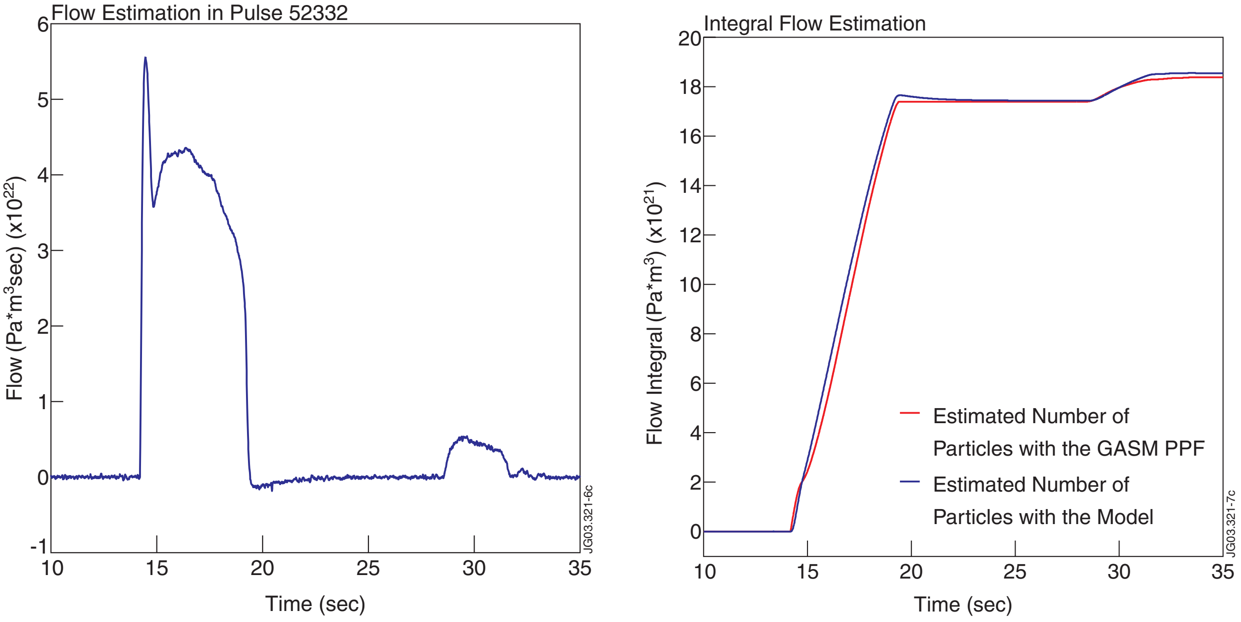

Figure 5: Example of the flow calculation and check of the accuracy of the flow estimation by comparison with the GASM PPF signal.