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Gas Flow Pattern Through a Long Round Tube of a Gas Fueling System (II)

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Gas fueling systems operated in the mode of a fixed valve opening at a constant line pressure, and the mode of a constant inlet flow are simulated to establish the relationships between the gas flow pattern and the tube dimensions under various system conditions.

Keywords : Gas fueling, Flow rate, Delay, Control valve, KSTAR

I. Introduction

A fueling system for the 1st plasma of the KSTAR(Korea Superconductor Tokamk Advanced Research) tokamak, which will be completed in the end of next year, is now under design. The 1st plasma of a tokamak is defined as a plasma generated by using a full basic engineering system at a minimum but meaningful power level. A fast feed-back control of gas fueling according to a change in the plasma density is usually not necessary at this stage, and thus, the mode of a fixed valve opening at a constant gas supply line pressure, and the mode of a constant inlet flow may be the primary candidates of the KSTAR fueling scheme. Both fueling modes use a control valve whose conductance can be changed in a timely manner, and they have similar operating characteristics. However, the latter one needs a kind of slow feed-back control to maintain a gas flow at a constant level.

Key parameters for designing a fueling system are the peak flow rate, the delay time, and the pulse duration. A unique set of values for the three parameters produces a unique gas flow pattern. The gas flow pattern can be properly controlled by adjusting the gas supply parameters and the tube dimensions. The peak flow rate is mainly determined by the gas supply parameters such as the gas supply line pressure and the valve conductance. The delay time can be roughly considered as the time taken to fill up the gas transferring tube, therefore, it depends on both the gas supply parameters and the tube dimensions. The gas pulse duration is composed of the delay time, the flat-top time, and the decay time. It is expected that the decay time has a similar dependency on the system parameters to that of the delay time. The flat-top time is simply given by an opening interval of a control valve.

In this paper the dependences of the delay time and the peak flow rate of a fueling system, which is operated in the mode of a fixed valve opening or the mode of a constant inlet flow, on the gas supply parameters and the tube dimensions are investigated. The relationships are definitively expressed by functional forms.

II. Numerical Simulation

A schematic drawing of a fueling system which can be operated in two different modes is illustrated in Fig. 1. The two fueling modes are nearly

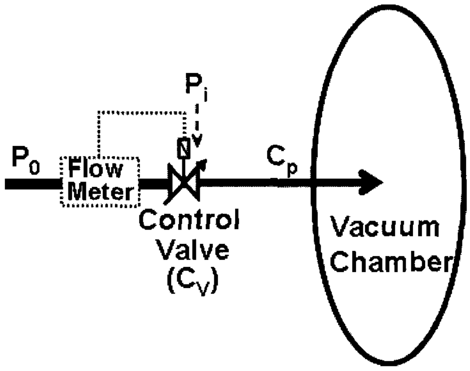


Fig. 1. Schematic drawing of a fueling system with a control valve. Dotted lines are for the mode of a constant inlet flow.

the same as each other except that the constant parameter is the line pressure or the inlet flow rate. The following time-dependent non-linear partial differential equation is established for a gas flow in a tube of a uniform cross-section. [1,2]

$$\frac{\partial P(x,t)}{\partial t}=\frac{\partial}{\partial x}\left(\frac{C_u(x,t)}{A}\frac{\partial P(x,t)}{\partial x}\right) \quad (1)$$

where P is the pressure in the tube, C_u is the pressure-dependent conductance of the unit length, and A is the inner cross-sectional area of the tube. C_u [m^3/s] is given by Eq. (2) of reference [2], which is applicable to the whole pressure regime from a molecular flow to a viscous laminar flow.

The gas flow rate at the tube exit is calculated by Eq. (2)

$$q(L,t)=-\left[C_u\frac{\partial P(x,t)}{\partial x}\right]_{x=L} \quad (2)$$

When the gas supply line pressure is constant at P_0, the boundary condition at the entrance of the tube(x=0) is given by

$$q(0,t)=C_v\,(P_0-P(0,t)),\ \ t\geq 0, \quad (3)$$

where $q(0,t)$ is the flow rate at the tube inlet and C_v is the conductance of a control valve.

On the other hand, when the inlet flow rate is constant at q_0, the boundary condition at the tube inlet is given by

$$q(0,t)=-\left[C_u\frac{\partial P(x,t)}{\partial x}\right]_{x=0}=q_0 \quad (4)$$

The boundary condition at the tube exit($x=L$) is expressed as $P(L,t)=P_{ch}(t)$ regardless of the fueling mode, where P_{ch} is the chamber pressure. The initial condition is given as $P(x,0)=P_{ch}(0)=P_{ch0}$. Solving Eq. (1) numerically with the boundary conditions and given values of C_v and A, the dependency of a gas flow pattern on the tube dimensions and the gas supply parameters can be obtained.

In the calculations the line pressure of the hydrogen gas is fixed at 1013 mbar or varied from 500 mbar to 2000 mbar in three steps, C_v is from 10^{-6} to 1 ℓ/s in four steps, and q_0 is from 0.1 to 10^5 sccm(0.00182~1816 mbar · ℓ/s at 20℃) in seven steps. Under usual fueling demands and pumping conditions, P_{ch} can be safely set at zero.

III. Results and Discussions

A. Mode of fixed valve opening

The delay time(t_{delay}) of a gas flow in a simulation is defined as the time when the gas flow rate at the tube exit reaches 90% of that at the tube inlet. t_{delay} is roughly expressed as V_p/C_p, where $V_p(\sim D^2L)$ is the inside volume of a tube, and C_p [$\sim D^nL^{-1}P_i^m$, where, {n,m} is {4,1} for a viscous flow and {3,0} for a molecular flow, and $P_i=P(0,\infty)$] is the conductance of a tube of length L. Therefore, the relation $t_{delay}\sim D^{-1}L^2$ is obtained for a molecular flow, which is independent of C_v and P_0. For a viscous flow, because

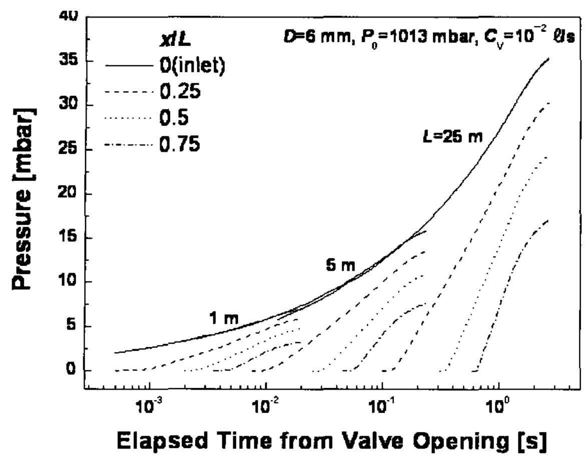


Fig. 2. Time variations of the pressure in a tube of diameter 6 mm for three values of the tube length at a fixed line pressure of 1013 mbar and with a fixed valve opening of 0.01 ℓ/s.

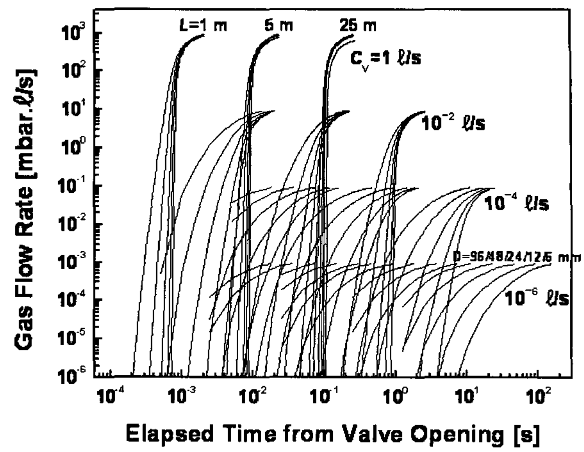


Fig. 3. Time variations of the flow rates at the tube exit for various system parameters at a fixed line pressure of 1013 mbar.

$P_1=P_0/(1+C_p/C_v)\sim[P_0C_v/(D^4/L)]^{0.5}$, it is expected that $t_{delay}\sim D^{-2}L^2P_1^{-1}\sim L^{1.5}C_v^{-0.5}P_0^{-0.5}$, which is independent of D. The maximum flow rate(q_{max}) at a steady state($t=\infty$) is given by $q_{max}=P_0(C_vC_p/(C_v+C_p)\sim P_0C_v(\equiv q_1)$. q_1 is the initial flow rate if assuming $P(0,0)=0$.

Fig. 2 shows the temporal variations of the pressures at three different positions in a tube at a fixed line pressure of 1013 mbar. The pressure at each position is increasing up to its maximum during a time lag which becomes longer when the position is more distant from the tube inlet. Fig. 3 presents the time variations of the flow rate at the tube exit for various system parameters at a fixed line pressure of 1013 mbar. End point of each curve corresponds to t_{delay}. All the curves are divided into groups depending on the valve conductance and the tube length. The dependency on the tube diameter is manifested more clearly at a lower inlet flow.

Two examples of the temporal evolution of the pressure profile in a tube from $t=0$ to $t=t_{delay}$ at

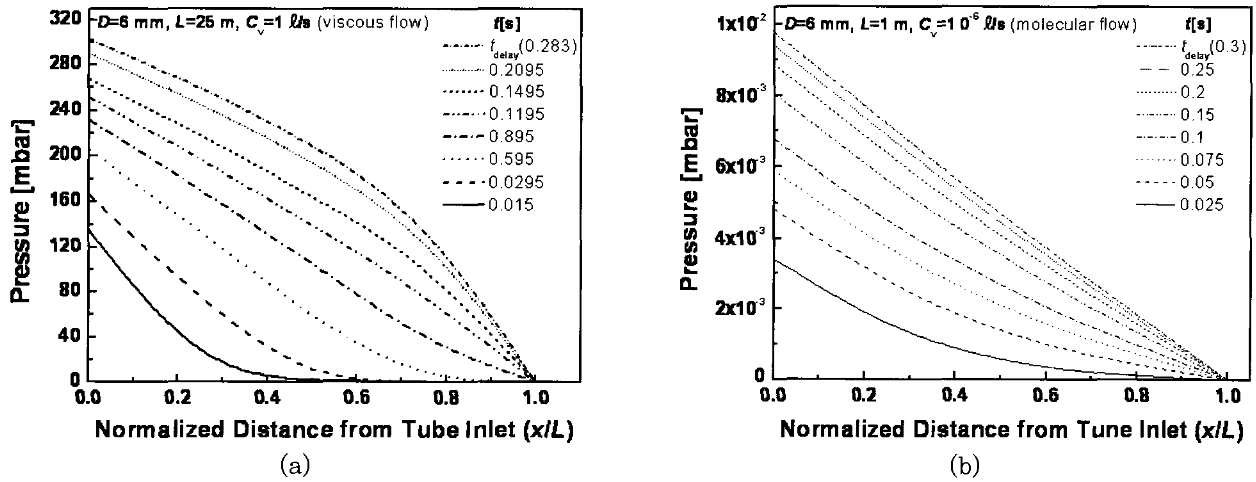


Fig. 4. Temporal evolution of the pressure profile in a tube from t=0 to t=t90% for a) a viscous flow and b) a molecular flow regimes.

two different flow regimes are described in Fig. 4. All the pressure profiles have monotonic negative gradients. For a molecular flow, where the conductance in the tube can be considered as a constant, the second derivative of a pressure profile always has a negative value, because the pressure continuously increases at any position and any time up to $t=t_{\text{delay}}$. For a viscous flow, a pressure profile changes gradually from a negatively convex one to a positively convex one when approaching a steady state. However, it does not mean that the tube pressure starts to decrease, because it is caused by the fact that the unit conductance in a tube is proportional to a local pressure.

Fig. 5 shows the dependency of the delay time (t_{delay}) on the valve conductance for different sets of tube dimensions. t_{delay} can be expressed as a decreasing function of the valve conductance like $t_{\text{delay}} \sim C_v^{-0.5}$ when C_v has a sufficiently large value. t_{delay} becomes saturated at a low value of C_v especially for a thick tube, where the gas flow can easily turn into a molecular one because of a low pressure level in a tube.

The relationship between t_{delay} and the tube length is plotted in Fig. 6 for twenty sets of valve conductances and tube diameters. t_{delay} is nearly proportional to the square of the tube length for a small valve conductance and for a thin tube. t_{delay} for a large valve conductance and/or a thick tube, where the gas flow is in a viscous regime, is proportional to $L^{1.5}$. As clearly shown in Fig. 7,

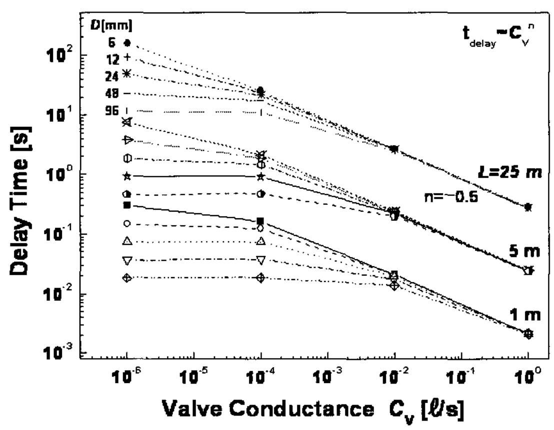


Fig. 5. Dependency of the delay time on the valve conductance for different sets of tube dimensions.

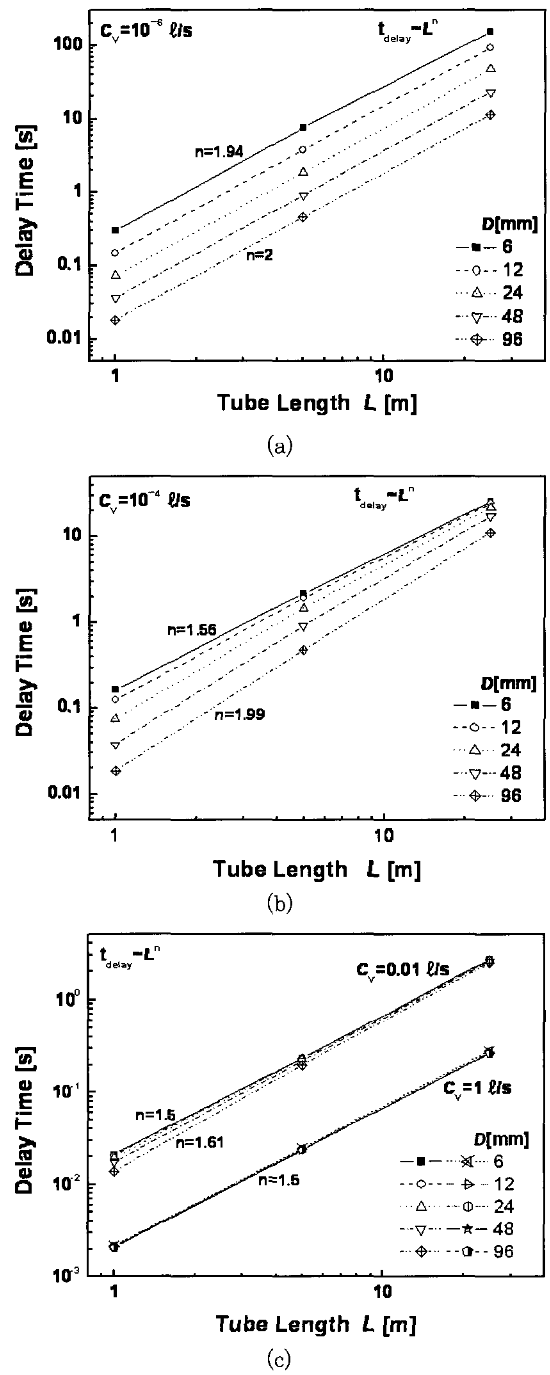


Fig. 6. Relationship between the delay time and the tube length for valve conductances of a) 10^{-6}, b) 10^{-4}, and c) 10^{-2} and 1 ℓ/s.

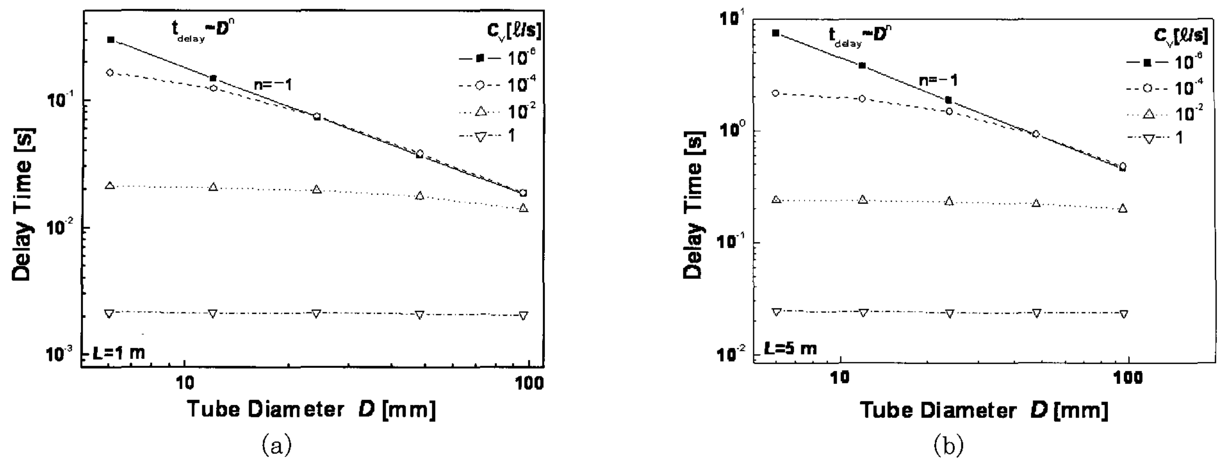


Fig. 7. Dependency of the delay time on the tube diameter for tube lengths of a) 1 and b) 5 m.

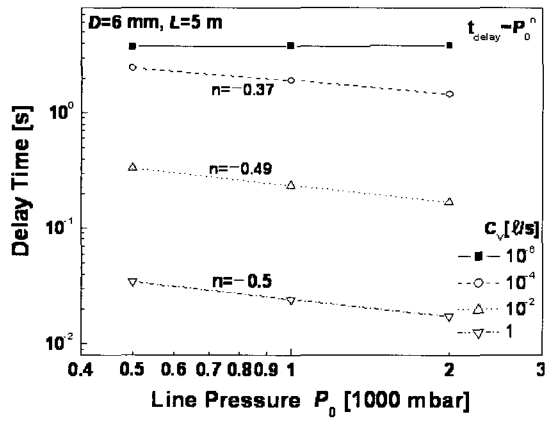


Fig. 8. Relationship between the delay time and the line pressure for a 6 mm thick and 5 m long tube.

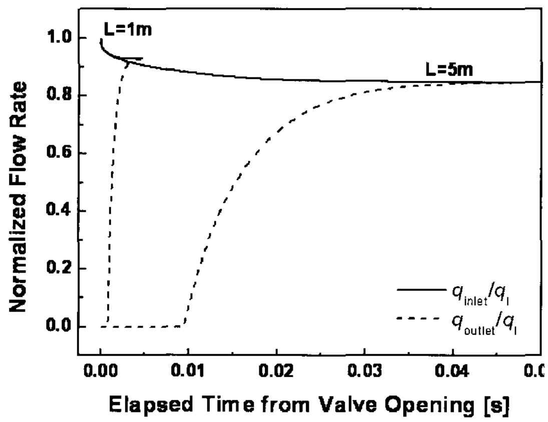


Fig. 9. Time variations of the inlet and outlet flow rates normalized to the initial flow rate qI.

t_{delay} is nearly independent of the tube diameter for a viscous flow, because an enlargement of the tube diameter causes an increment in the tube volume as well as an increase of the tube conductance. The relation $t_{delay}{\sim}D^{-1}$ is obtained for a small valve conductance, and for a thick and short tube.

Fig. 8 shows the relationship between t_{delay} and the line pressure for a 6 mm thick and 5 m long tube. t_{delay} is inversely proportional to the square root of the line pressure for a large valve conductance, and becomes independent of the line pressure as the valve conductance decreases.

The maximum flow rate in the steady state (q_{max}) at the tube exit is less than the initial flow rate at the tube inlet, because the pressure drop through a control valve and the inlet flow rate are not fixed but gradually decreasing up to steady state values. Fig. 9 shows the time variations of the inlet and outlet flow rates normalized to the initial flow rate q_I. The two flow rates eventually coincide with each other at a steady state value. A reduction in the steady state flow rate is increased with the tube length.

Fig. 10 presents the dependency of q_{max} on the valve conductance for tubes of 6 mm and 12 mm thick, and 1~25 m long. A larger valve conductance, and a thinner and longer tube lead to a

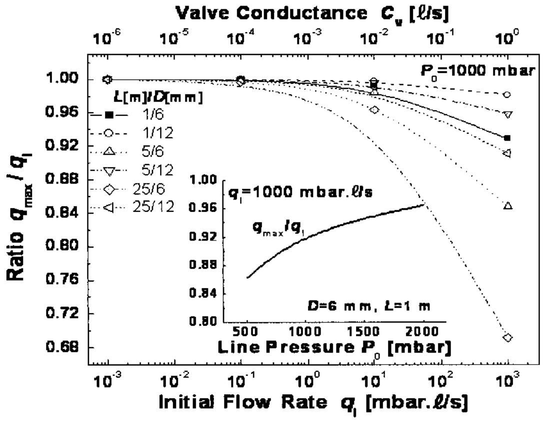


Fig. 10. Dependency of the steady state flow on the valve conductance for the tubes of 6 and 12 mm in thickness, and 1~25 m in length.

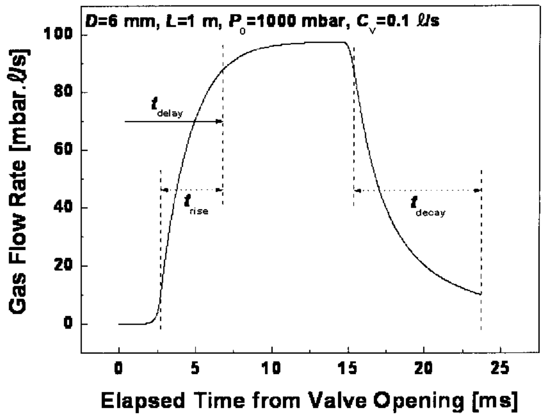


Fig. 11. Example of the gas flow pattern through a tube.

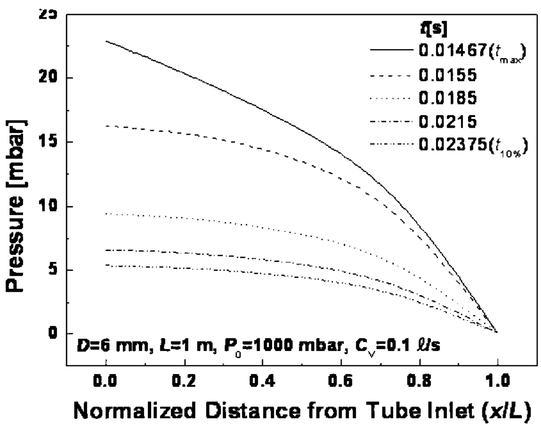


Fig. 12. Temporal evolution of the pressure profile in a tube after closing the valve.

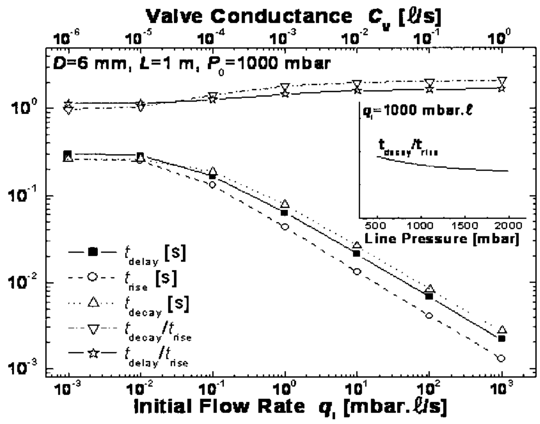


Fig. 13. Comparison of t_{delay}, t_{rise}, and t_{decay} for a 6 mm thick and 1 m long tube from the molecular flow to the viscous flow.

larger decrease of q_{max}, which is due to a larger pressure drop. For a 12 mm tube, the decrease of q_{max} is not much and it can be safely considered to be the same as the initial flow rate. The inside graph in Fig. 10 indicates that a higher line pressure results in a higher q_{max} at a fixed initial flow rate, because the line pressure is the driving force of the gas flow through a tube.

A pressure pulse is generated by switching on and off a control valve. If the valve is closed after a gas flow has reached a flat-top, the gas flow starts to decrease with a characteristic decay time constant(refer to Fig. 11). The pulse duration is approximately the summation of the rise time, the flat-top time and the decay time. The decay time is defined as the interval between the time when the pressure drop is 10% of its maximum value and the time of a 90% drop.

The rise time(t_{rise}) and the decay time(t_{decay}) are also proportional to V_p/C_p like the delay time (t_{delay}). However, the pressure-dependent conductance C_p in the decaying stage would be considerably different from that in the rising stage. Fig. 12 presents the time evolution of the pressure profile after closing the valve for a 6 mm thick and 1 m long tube. The pressure profile is positively convex all the time in contrast to that at the rising stage. Thus the average pressure in the decaying stage is less than that in the rising stage at a similar flow rate.

t_{delay}, t_{rise}, and t_{decay} are compared in Fig. 13 for a 6 mm thick and 1 m long tube. t_{decay} is nearly the same as t_{rise} for a molecular flow where C_p is independent of the pressure. However, t_{decay} is nearly twice as much as t_{rise} for a viscous flow, where the average pressure and consequently the tube conductance in the decaying stage is much lower than those in the rising stage. t_{rise} is around 90% of the delay time at a molecular flow regime, but becomes much short to 60% of the delay time for a viscous flow regime, because it takes more time to attain a 10% rise when the pressure is still low at the beginning of a gas pulse. The small figure inserted in Fig. 13 indicates that a higher line pressure produces a relatively shorter decay time, which is closely related with the inside figure of Fig. 10. This is based on the fact that at a higher line pressure, the pressure level and the conductance in the tube also become higher.

All the calculation results for the dependency of the time constants in a gas flow can be summarized as follows;

$$\begin{aligned} t_{delay} &\sim L^{1.5} C_v^{-0.5} P_0^{-0.5} \text{ for } viscous\ flow, \\ &\sim D^{-1} L^2 \text{ for } molecular\ flow, \\ &\approx \beta D^{-m} L^n P_0^{-k} C_v^{-j},\ 0 \le m \le 1,\ 1.5 \le n \le 2, \\ &\qquad 0 \le k \le 0.5,\ 0 \le j \le 0.5, \end{aligned} \tag{6}$$

$$\begin{aligned} & t_{rise} \lesssim 0.9\, t_{delay},\ t_{decay} \gtrsim t_{rise}, \\ & q_{\max} \lesssim C_v P_0 \end{aligned} \tag{7}$$

β is a proportional constant. The equal signs are satisfied when a gas flow is at a fully viscous regime or a fully molecular regime.

B. Mode of constant inlet flow rate

For a molecular flow, the relation $t_{delay} \sim D^{-1}L^2$ is satisfied in this case too. If the inlet flow rate is fixed at q_0, for a viscous flow, because $P_1 = q_0/C_p \sim (q_0/(D^4/L))^{0.5}$, $t_{delay} \sim D^{-2}L^2P_1^{-1} \sim L^{1.5}q_0^{-0.5}$, which is independent of D. These relations are basically the same as those of the previous section, if noting that $q_1(=P_0C_v)$ is in principle equal to q_0. And then, the simulation results are also similar to those of the fixed valve opening mode except for some minor differences.

Fig. 14 shows the dependency of the delay time (t_{delay}) on the inlet flow rate for different sets of tube dimensions. t_{delay} of the gas pulse is a decreasing function of the inlet flow rate, that is, $t_{delay} \sim q_0^{-1}$ for a large value of q_0. However, t_{delay} becomes saturated at a low q_0 especially for a thick tube, where the gas flow is usually in a molecular regime.

The relationship between t_{delay} and the tube length is plotted in Fig. 15. t_{delay} is nearly proportional to the square of the tube length for small values of q_0 and for thin tubes. t_{delay} for a large q_0 and/or a thick tube is proportional to $L^{1.5}$. t_{delay} is nearly independent of the tube diameter

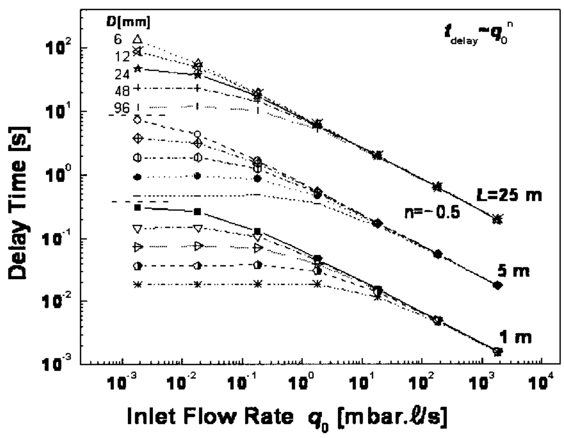


Fig. 14. Dependency of the delay time on the inlet flow rate for different sets of tube dimensions when the inlet flow rate is constant.

as shown in Fig. 16 except that t_d is proportional to D^{-1} for a small q_0, and for a thick and long tube.

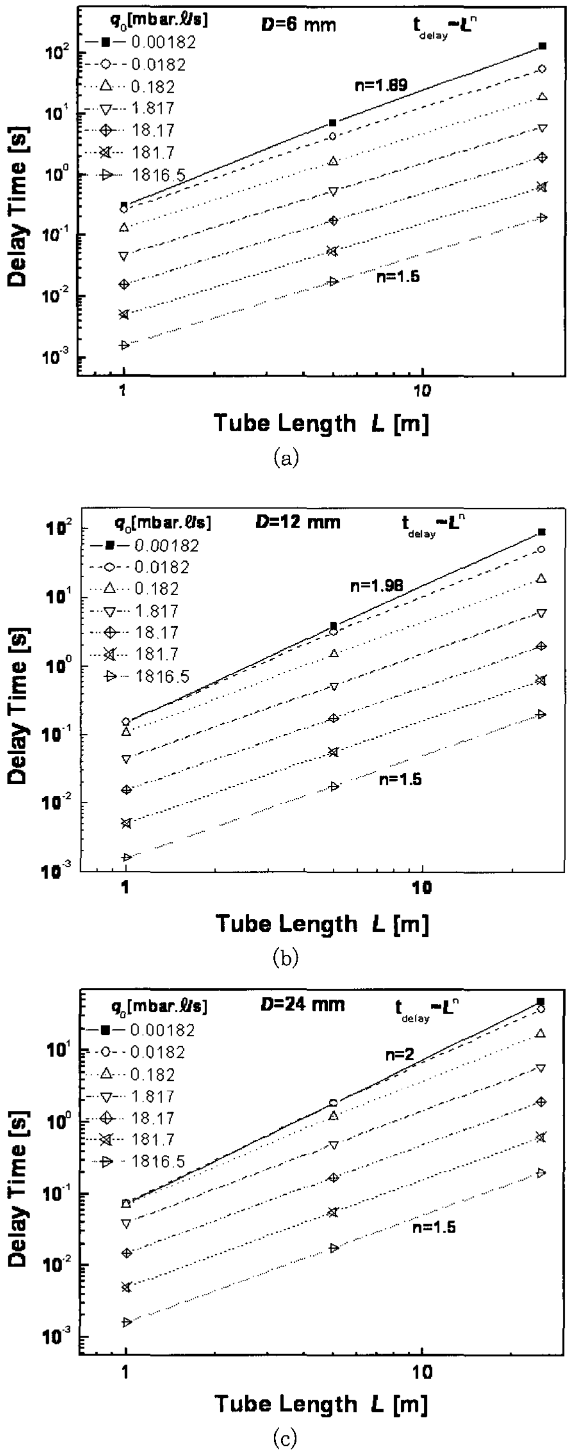


Fig. 15. Relationship between the delay time and the tube length for tube diameters of a) 6, b) 12, and c) 24 mm.

All the calculation results for the dependency of the delay time in the gas flow on the system parameters can be summarized as follows;

$$t_{delay} \sim L^{1.5} q_0^{-0.5} \text{ for } viscous\ flow,$$

$$\sim D^{-1} L^2 \text{ for } molecular\ flow,$$

$$\approx \delta D^{-m} L^n q_0^{-k},\ 0 \le m \le 1,\ 1.5 \le n \le 2,\ 0 \le k \le 0.5.$$

δ is a proportional constant. The equal signs are satisfied when the gas flow is at a fully viscous regime or a fully molecular regime.

IV. Application

The construction of the KSTAR tokamak will

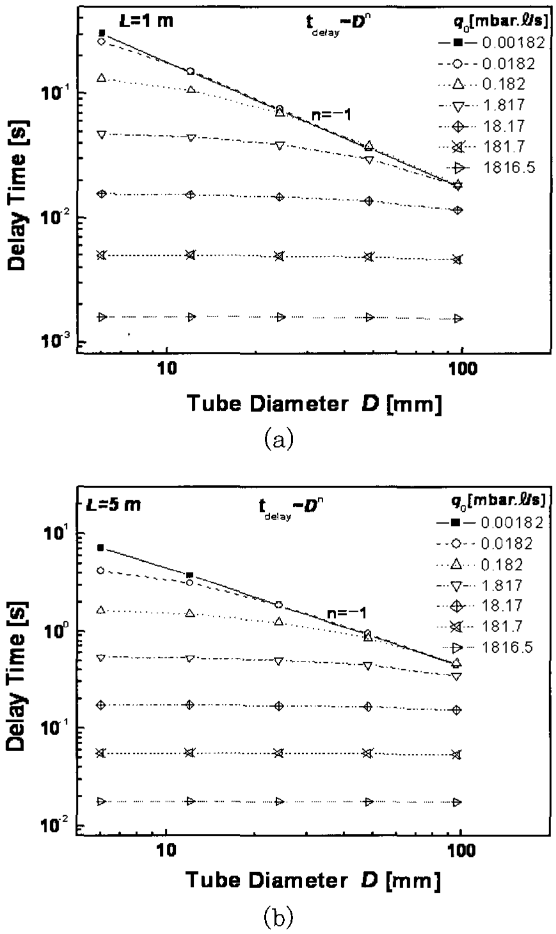


Fig. 16. Dependency of the delay time on the tube diameter for tube lengths of a) 1 and b) 5 m.

be completed by the end of 2007, and the 1st plasma will be publicly displayed after a commi-ssioning stage of 6 months. The vacuum vessel of the KSTAR tokamk is encased by a cryostat and the shortest access to the plasma chamber is 2 m. The fueling system for the 1st plasma is now under design to be a pre-programmed valve opening type without a feed-back control. The requirements on the gas fueling, which is based on an ECH(electron cyclotron heating) assisted start-up scenario [3], are as follows; q_{max}=150 mbar · /s, t_{delay}=2 ms, and pulse duration=5 ms.

If assuming that the fueling system will be

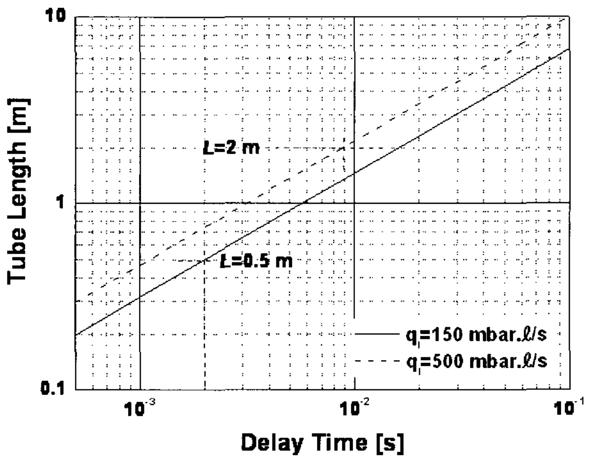


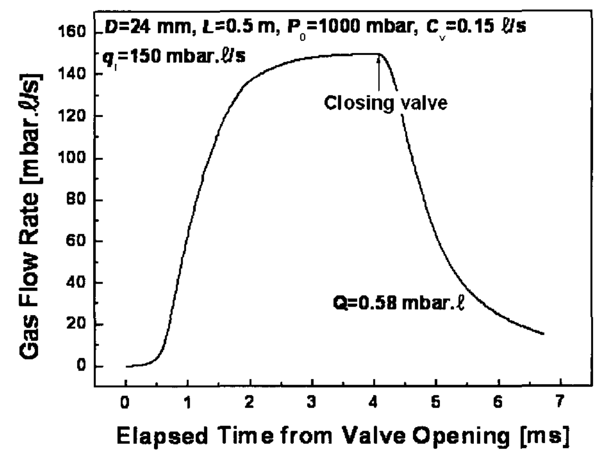
Fig. 17. Graph showing allowable values of the tube length to satisfy the fueling re-quirements.

operated in a viscous laminar flow regime where the parametric relationships are well defined and relatively short time lags are obtained, β in Eq. (6) can be determined by using simulation results.

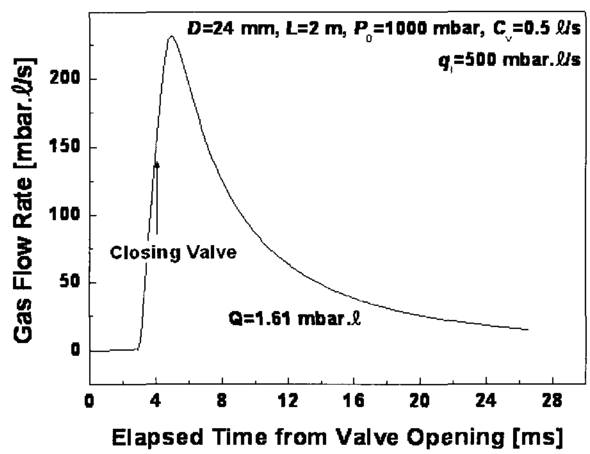
From a data point{t_{delay}=0.002456 s} on a graph in Fig. 4 or Fig. 5 for a typical parameter set{L= 5 m, P_0 = 1013 mbar, C_v =1 ℓ /s}, the value of β is determined to be 0.0699. From Eq. (6) and Eq. (7), L is calculated to be 0.5 m. One of the rea-sonable solution sets for P_0 and C_v is {1000 mbar, 0.15 ℓ /s}. To fulfill the condition L=0.5 m, the control valve should be located inside the vertical port. If the tube length must be 2 m or more, there is not a simple solution to satisfy the requirements(see Fig. 17). A complicated but re-asonable solution is to set q_I(=$P_0 C_v$) much larger (for example, 500 mbar · ℓ /s) than the required one and to close the control valve at the time when the flow rate approaches a target value. Fig. 18 shows the gas pulse shapes generated by the two solutions.

V. Conclusions

The operating characteristics of the gas fueling system composed of a control valve, and a gas



(a)



(b)

Fig. 18 Gas pulse shapes for two possible solutions when a) L=0.5 m and b) L=2 m.

transferring tube were simulated by a numerical calculation. All the calculation results indicated that the relationships between the gas flow pattern(the delay time, the maximum flow rate) and the system parameters(the line pressure, the valve conductance, the tube length, and the tube diameter) were in principle identical to those analytically expected.

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기체연료주입계의 긴 원형도관에서 기체 흐름의 유형 (2)

인 상 렬

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(2006년 7월 12일 받음)

일정한 기체 공급 압력에서 정해진 만큼 밸브를 개방하는 방식과 밸브를 조절하여 일정한 유량을 흐르도록 하는 두 가지 기체 주입 방식의 작동특성에 대한 시뮬레이션을 통해 공급 압력, 밸브 컨덕턴스, 유량 등 시스템 조건 및 기체 수송관의 길이와 굵기에 따라 기체흐름의 유형이 어떻게 바뀌는지 조사했다.

주제어 : 기체 연료 주입, 유량, 지연시간, 조절 밸브, KSTAR

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