Applying control volume finite element for modelling

Direct injection boom spraying flow

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Abstract. Assessment of injection lag transport and uniformity of direct injection boom sprayer is an important issue for successful variable rate spraying technology. To estimate the boom lag transport and pressure loss, a numerical model is formulated on the basis of fluid hydrodynamic conservation equations. The software is implemented in visual basic. To solve the pressure – velocities equations, control volume finite element method (CV) is used to delimit elementary volumes of the boom. Linearization of the conservation laws is ensured by considering discrete form of the equations and calculating velocity and pressure step by step throughout the whole boom. The flow behaviour is simulated into a boom section divided into N elementary volumes, each of them including one nozzle.

To test the model, three boom diameters (5, 6 and 8 mm) and two chemical viscosities (10^{-6} and 10^{-5} m^2/s) were used. Experimental trials are carried out on boom having 2.5 m length (5 nozzles) for measuring pressure gradient and lag transport. Results showed that the model can predict the pressure losses and the lag transport accurately (error within 5%) to optimize boom designs.

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Keywords. Direct injection, control volume method, lags transport, friction losses, viscosity.

Introduction

Direct injection system (DIS) can be very interesting to apply pesticide accurately and safely. In fact, control of concentration proportionally to forward speed is probably the best solution for solving misapplication that occurs with conventional sprayers. However, DIS advantage is still conditioned by material performance, especially the ability to apply the desired pesticide rate and setting it in real time. The performance can be evaluated mainly through material efficiency to control and to maintain desired mixture concentration. Practically, adjusting applied concentration to forward speed variation or to a new set-point needs to be carried at minimal possible time delay.

The response time is a critical parameter for evaluating DIS accuracy. It has two main components. The first one is related to the transport time between the injection point and the nozzles. The second component is the response characteristic of the injection metering system (Paice & al., 1995). The transport lag depends mainly on optimization of hydraulic boom layout when injection point is located closely to the centre of the boom line. The use of electrical energy to supply DIS pump gives possibility to avoid any significant complementary lag time amplification and limits it only to boom scheme. Paice & al. (1997) used two transient characteristics, time constant and rise time, to evaluate the dynamic response of a sprayer. The time constant is the time required to reach 63.2 % of the step input while the rise time is the time required to go from 10 to 90 % of the step input.

The DIS boom design needs to be computed efficiently, not only to maximize fluid flow for obtaining short lag time and turbulent flow regime for improving online mixing, but also to contain friction losses that cause pressure decrease and affects nozzles uniformity along boom (Vondrika & al, 2007). Moreover, variability of pesticide viscosity can potentially increases friction losses and affects slightly boom jet uniformity when heavy pesticide is applied at low temperature conditions. In fact, liquid pesticides formulations have large magnitude of viscosity from 1 mPa.s to 1000 mPa.s. Although, the most commercialised formulations have dynamic viscosity under 100 mPa.s (Hloben, 2007). Studying viscosity effect of sprayed mixture helps to approach potential hydraulic impact on boom pressure drop.

To study boom flow behaviour for optimal DIS design, three points should be detailed:

- The optimal hydraulic boom structure to obtain fast response to establish concentration equilibrium and minimal pressure drop that keeps acceptable nozzles uniformity.
- The discrete profile of lag time and turbulence along standard boom layout of constant diameter.
- The potential effect of sprayed mixture viscosity in relation to friction losses in DIS boom.

The objective of this study was:

- To develop numerical model based on finite volume method to characterise mixture flow in DIS boom.
- To design DIS laboratory bench based on two boom layouts of ten nozzles (serial and parallel tip nozzles scheme) in order to compare simulated results with experimental data.

Material and methods

Model Approach

The model is developed to carry out discrete scheme of DIS boom hydraulic flow by using finite volume method (Reddy, 1993, Lakhdar & al, 2006). It takes advantage of physical and chemical parameters of boom and the sprayed mixture; width, diameter, pipe material roughness, number of nozzles, nozzle flow rate coefficient, upstream boom pressure, downstream boom pressure, linear and local friction losses, density and viscosity. As results, the model gives a numerical gradient scheme of pressure, flow speed, Reynolds number, friction loss and lag time for each control volume (CV) and then for lateral boom section. The used numerical method is based on iterative incremental search (James & al., 1993) for solving non linear algebraic equations of pressure and flow rate. To compute friction losses, the Darcy-Weisbach friction losses model (Sullivan, 1989; Gleen, 2003) was used and the Newton-Raphson numerical method was applied to yield friction factor in Colebrook equation.

The discrete computation consists of application of mass and energy conservation equations on elementary CV that contains one nozzle body of DIS boom sprayer (Figure 1).

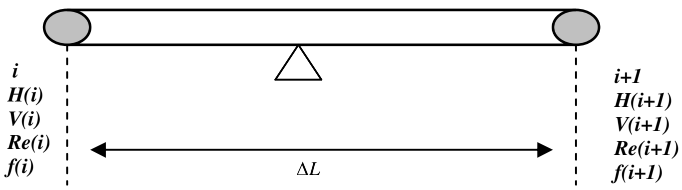

Figure 1. Arbitrary control volume (i) and upstream and down stream parameters: pressure (H), flow speed (V), Reynolds number (Re) and friction factor (f) applied for numerical computation

- Computation of nozzle flow rate average $\overline{q}$ at control volume i depends on upstream pressure Hi, downstream pressure $Hi+1_i$, nozzle flow rate coefficient (k) and pressure exponent (x):

$$\overline{q}_i = k\overline{H}^x \quad \Rightarrow \overline{q}_i = k\left[\frac{H_i + H_{i+1}}{2}\right]^x \quad (1)$$

- Mass balance computation at control volume i depends on upstream and downstream flow rate (or on pipe section area A and upstream V(i) and downstream V(i+1) flow speeds) and on nozzle flow rate:

$$A.V_i = A.V_{i+1} + \overline{q}_i \quad \text{And} \quad A = \pi d^2 / 4 \qquad (2)$$

$$V_{i+1} = V_i - \left(4\overline{q}_i / \pi d^2\right) \qquad V_{i+1} = V_i - \left(4/\pi d^2\right).\left(\frac{H_i + H_{i+1}}{2}\right)^x \quad (3)$$

- Energy balance computation at control volume i is based on Bernoulli theorem. It depends mainly on hydrostatic pressure, kinetic energy and induced friction loss between input and output points of CV (potential energy keeps zero for horizontal boom position):

$$H_i + \frac{V_i^2}{2g} = H_{i+1} + \frac{V_{i+1}^2}{2g} + \Delta Hf_{i,i+1} \Rightarrow H_{i+1} = H_i + \frac{V_i^2}{2g} - \frac{V_{i+1}^2}{2g} - \Delta Hf_{i,i+1} \quad (4)$$

- Friction loss computation for CV of ΔL length is based on Darcy-Weisbach equation and depends on upstream and downstream linear friction factors (f(i) and f(i+1)) and minor loss factor ξ at nozzle body level :

$$\Delta Hf_{i,i+1} = \frac{1}{2g}\left[\left(\frac{f(i) + f(i+1)}{2}\right)\frac{\Delta L}{d} + \xi\right]\left(\frac{V_i + V_{i+1}}{2}\right)^2 \qquad (5)$$

- Friction factor f(i) computation depends on flow regime:
  - For laminar and transitory flow (Re≤3000), f(i) depends only of Reynolds number:

$$\mathrm{Re}(i) = \frac{dV_i}{\mu} \qquad f(i) = \frac{64}{\mathrm{Re}(i)} \qquad (6)$$

  - For turbulent flow (Re>3000), f(i) can be computed by Colebrook equation and depends on Reynolds number and pipe absolute roughness (ε):

$$\frac{1}{\sqrt{f(i)}} = -2\log\left(\frac{\varepsilon}{3.7d} + \frac{2.51}{\mathrm{Re}(i)\sqrt{f(i)}}\right) \qquad (7)$$

For solving numerically the Colebrook equation, the model was implemented by Newton-Raphson iterative method subroutine. This method quickly yields f (i) values for minimal iteration number (James & al., 1993).

- Lag transport computation depends on input and output flow speeds and CV length:

$$T_{lag}(i) = \frac{\Delta L}{2}\left(\frac{1}{V_i} + \frac{1}{V_{i+1}}\right) \quad (8)$$

Input parameters

N: number of nozzles, L: boom width
d: boom diameter, Ra: absolute roughness
H_0: Upstream boom pressure
H_n, H_c: Simulated and computed values of downstream pressure
H_{nf}: Maximal simulated value of downstream pressure
p: pressure increment, W : iteration number
k: nozzle flow rate coefficient, x : nozzle pressure exponent
ρ: sprayed mixture density
µ: cinematic viscosity of sprayed mixture

1. Choice of sprayed mixture parameters (density and cinematic viscosity)
2. Loop for diameters boom choice (N diameters)
3. Choice of upstream boom pressure H_0 (pressure value indicated of input flow)
4. Loop of W iterations to increment H_n towards H_{nf} by pressure increment p
5. Loop of N (nozzles) iterations to compute hydraulic parameters for each CV:
   - nozzle flow rate from simulated pressure gradient
   - Flow speeds and Reynolds numbers in upstream and downstream CV levels
   - Friction losses coefficients in upstream and downstream CV levels (subroutine for solving numerically Colebrook equation based on Newton-Raphson iterative method)
   - Friction losses in CV (use of Darcy-Weisbach equation)
   - Lag transport in CV
   - Concluding computed pressure value from mass conservation equation
6. Computation of hydraulic parameters for boom section of N nozzles (CV)
7. Convergence test of simulated pressure value toward computed one from mass conservation equation

Output parameters

- Data sheet of hydraulic parameters results and convergence for each CV, each iteration and each boom case;
- Trend of convergence test showing simulated pressure, effective computed pressure, friction losses gradients and convergence point.

Figure 2. Scheme of computational algorithm

Boom designs simulation

For testing the model, three diameters (5, 6 and 8 mm) are simulated to study flow behaviour of DIS boom section of 5 serial nozzles. Moreover, two viscosities of 10^{-6} m²/s (water) and 10^{-5} m²/s (10 times more than water) are taken into account. The simulated cases resulted in numerical schemes of pressure gradient, nozzles uniformity, flow regime and lag transport that helped to approach boom quality application. The convergence test was based on simulating H_n value and incrementing it by step "p" toward H_{nf}. The optimal H_n for each boom diameter moved toward computed pressure H_c to satisfy the chosen convergence ratio (practically less than 10^{-3}). This ratio is the absolute value obtained by subtracting simulated pressure gradient ΔH_s (H_0-H_n) from computed pressure gradient ΔH_c (H_0- H_c).

The input parameters into model were:

For boom: **N** = 5, **L**= 2,5 m, **d**1= 8 mm, **d**2= 6 mm, **d**3=5 mm, **Ra**=2 um, **Ho**=30 m (3 bars), ξ=0.03

For nozzle flow rate: **k** = 10^{-5}, x=0.5, **q**= 2.10^{-5} m^3/s (Teejet XR 8003:1.2 l/mn ~ 3 bars),

For sprayed mixture: **ρ** = 1000 kg/ m^3, **µ**1= 10^{-6} m²/s (water), **µ**2= 10^{-5} m²/s (10 times more).

Experimental design

To assess model computation, two cases of serial and parallel boom layouts were studied (figure 3). Laboratory DIS equipped with main diaphragm pump (Flojet of Sherflo, 24V DC, 10 l/mn~2,8 bars), and peristaltic pump (Marlow Watson™ 400D/E, two channels, 38 ml/mn (x 2)) to inject fluorescein tracer at upstream point of the main pump. Pressure boom gradient was measured via two sensors (Sensorthechnics™ CTE 8005GY7, Pmax=5bars, non-linearity=0.1, hysteresis=0.015) mounted upstream and downstream boom sides. Lag transport was approached by five fluorometric sensors that were designed and calibrated to sense fluorescein transmittance at 520 um at each nozzle body (El Aissaoui & al.., 2007). To construct serial boom layout, commercial copper piping (d=6 mm, roughness~2 µm) was used to connect nozzles body mounted in tee junctions as shown in figure 4. Parallel boom layout was formed of quick connect flexible (Festo™, d= 4mm, roughness~ 2 um) to attach each nozzle body to the collector as shown in figure 3. A LabVIEW VI was implemented to acquire data by DAQ NI-USB6251 at sampling frequency of 5 Hz. Diaphragm and peristaltic pumps were actuated by PWM (2020S of CJ Controls LTD) to adjust concentration injection ratio, operating pressure and/or to induce step change.

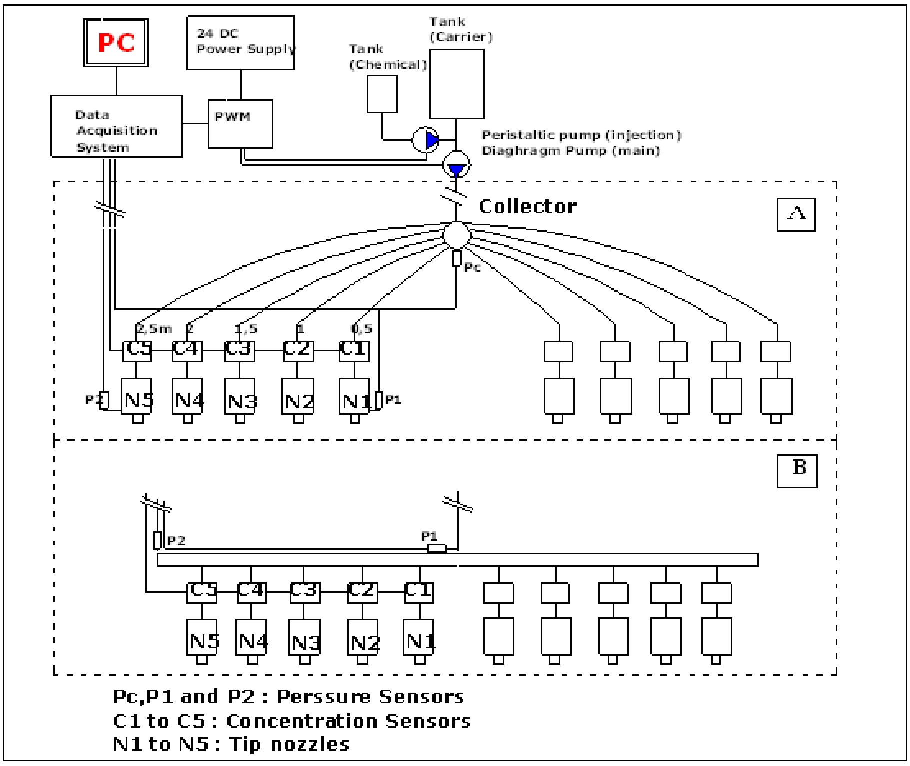

Figure 3 DIS laboratory bench based on two boom layouts of parallel (A) and serial (B) schemes

Results and discussion

Model computational results and discussion

The calculated model results (table 1) showed that 6 mm boom diameter could be satisfactory for keeping application uniformity up to 97% and short lag transport (dead time within 1.5 s for 2.5 m boom section length) in serial supply scheme. Prediction of viscosity effect showed that it kept non significant from 10^{-6} to 10^{-5} m^2/s to affect boom flow uniformity (within 1%). Otherwise, the choice of small diameter (less than 6 mm) could be also satisfactory to supplying nozzles separately from common collector in parallel scheme.

The calculated lag transport tended to increase exponentially from 9% (nozzle 1) to 43% (nozzle 5) as shown in figure 4. The fourth and fifth nozzles took 65% of total lag because of the low flow speed occurring at the boom end which caused long dead time and low gain to erase dead volume.

The calculated discrete profile of Reynolds number showed that the flow was kept turbulent (Re>3000) for good mixing. Furthermore, the viscosity affected considerably flow regime by decreasing Reynolds number.

Table 1: calculated results of serial boom layouts at 3 bars

Nozzles number	d (mm)	viscosity (m^2/s)	Convergence $\lvert\Delta H_s-\Delta H_c\rvert$	ΔH_c (m) (H_0-H_n)	$\Delta H_c/H_0$ (%)	ΔHf (m)	Lag transport (s)	Uniformity q_5/q_1 (%)
5	8	10^{-6}	0,00035	0,614	2,05	0,935	2,41	99,33
		10^{-5}	0,00049	0,991	3,30	1,312	2,40	98,91
5	6	10^{-6}	0,00027	1,958	6,53	2,664	1,50	97,40
		10^{-5}	0,00016	2,675	8,92	3,381	1,48	97,28
5	5	10^{-6}	0,00024	4,999	16,66	6,461	1,00	93,13
		10^{-5}	0,00003	5,696	18,99	7,157	0,99	92,11

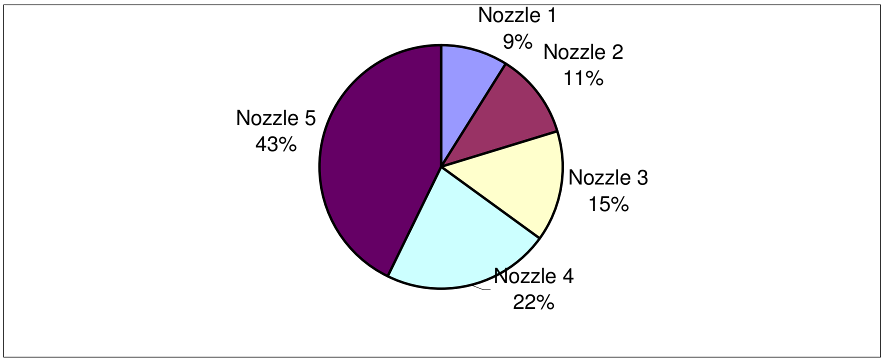

Figure 4 Discrete profile of lag transport in serial nozzles at 3 bars (6 mm diameter)

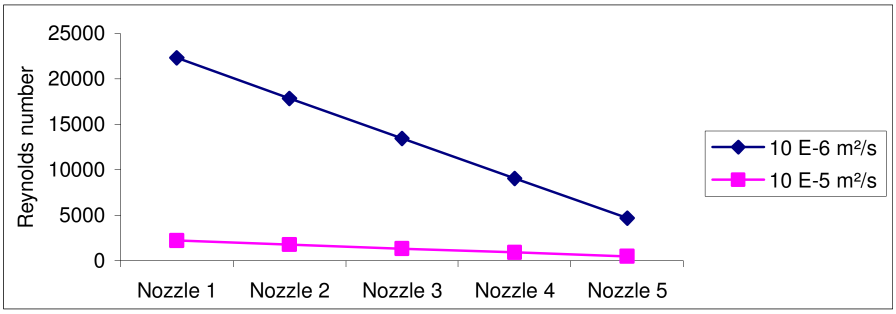

Figure 5 Discrete profile of Reynolds number in serial boom layout at 3 bars (6 mm diameter)

Experimental results and discussion

Pressure drop

The test of boom section of 5 serials nozzles (figure 6) showed that measured pressure drop kept around the simulated values (7% ± 1). The divergence at 1 bar can be explained by miss adaptation of the nozzle law at low pressure. Practically, the difficulty to predict accurately pressure gradient kept in approaching rightly minor losses that can occur in different junctions and in using sophisticated differential pressure sensors. Furthermore, simulated trends showed that nozzles number can affect pressure gradient significantly.

The test of the parallel boom layout (figure 7) was carried out by sensing pressure gradient between collector and the nearest nozzle (0.5 m) and between collector and the farthest nozzle (2.5m). The pressure gradient between the upstream and downstream nozzles kept around 7% ± 1.

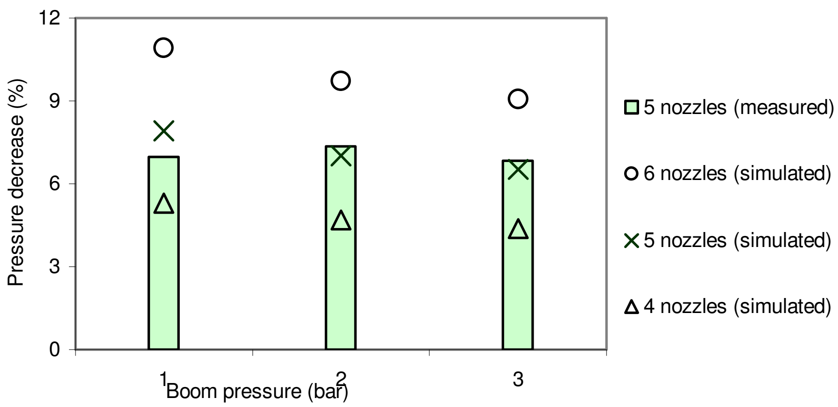

Figure 6: Pressure drop in serial boom layout (diameter of 6 mm)

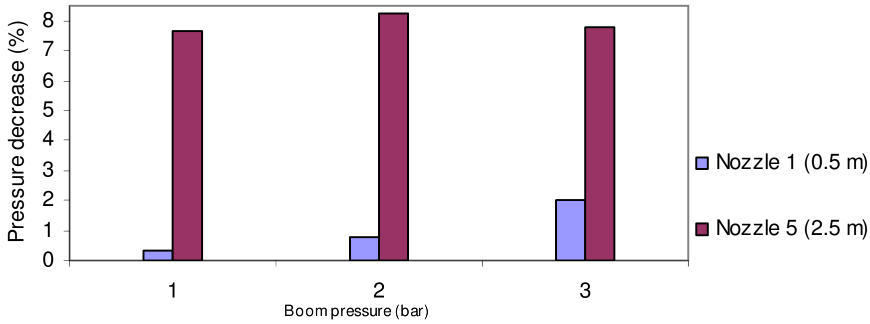

Figure 7: Pressure drop measured in parallel boom layout (diameter of 4 mm)

Lag transport

To characterize lag transport of serial and parallel boom layout, three parameters were used, dead time, time constant and rise time. The first time is delay from start input point to the start of response which depends on dead volume and flow speed in each CV. The second one is time required to reach 63.2% of concentration change. The third one is time needed to go from 10 to 90% of step change.

The measured lag transport of the five nozzles mounted in serial layout was about 4.5 s as shown in figure 8. The dead time moved upward from 0.3 s (Nozzle 1) to 1.8 s (Nozzle 5). The time constant changed from 1 s (Nozzle 1) to 1.3 s (Nozzle 5). The rise time increased slightly to form different S-shaped curves.

The total lag transport of the five parallel nozzles kept around 4 s. Dead time stepped constantly from 0.4 s (nozzle 1) to 2 s (Nozzle 5). The time constant kept constant for the five nozzles around 0.9 s. The rise time took the same value of 1.2 s for the five nozzles, forming similar S-shaped curves as shown in figure 9.

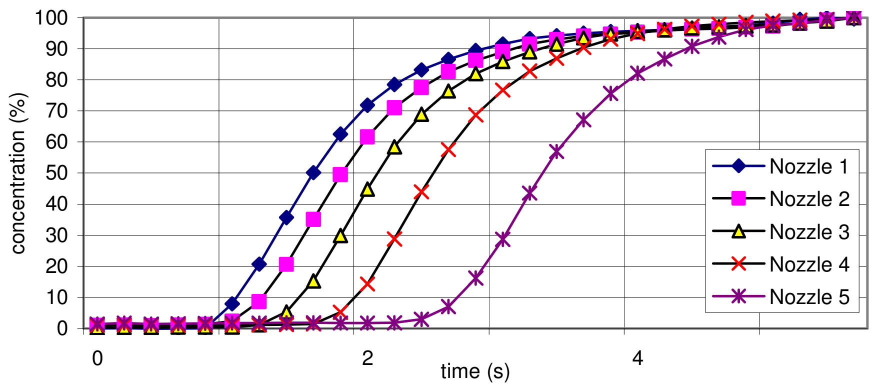

Figure 8: Response of 5 serial nozzles to step change at 3 bars (diameter of 6 mm)

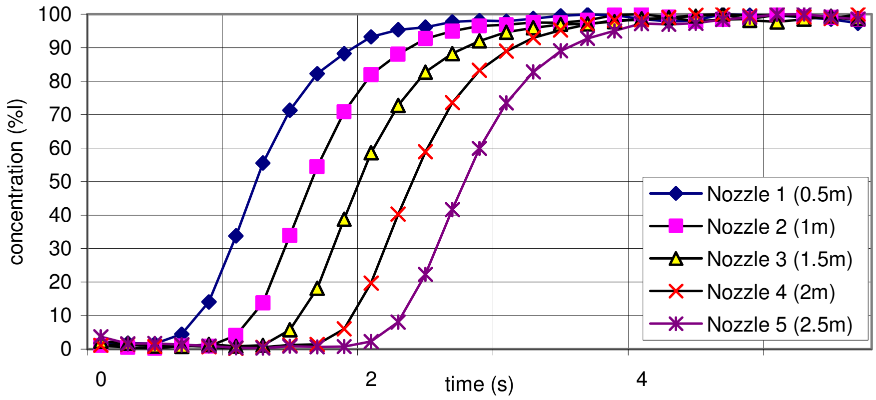

Figure 9 Response of 5 parallel nozzles to step change at 2.7 bars (diameter of 4 mm)

Conclusion

The ability of the developed model to predict discrete hydraulic profile by applying control volume element method, helps design optimal boom scheme. The model accuracy keeps conditioned by the miss adaptability of the Darcy-Weisbach model to compute friction losses in transitory flow regime band flow and by the difficulty to approach accurately the minor losses occurring actually in boom line. The comparison between serial boom layout and parallel boom layout showed how it was interesting to consider the effect of many lags in series and in parallels, coupled and uncoupled lags, on boom dynamic response.

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