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ANALYSIS OF THE CAVITATING FLOW IN REAL SIZE DIESEL INJECTORS WITH FIXED AND MOVING NEEDLE LIFT SIMULATIONS

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Abstract. *For Diesel engines, the determination of the exit conditions of the injector nozzle flow is of great importance because it greatly influences the spray development inside the combustion chamber and hence the combustion process. In addition, it is relevant to know the flow conditions to provide the initial conditions for spray models. Since the possibility of experimentally observing and measuring the flow inside real size Diesel injectors is very limited, CFD calculations are generally used to obtain the relevant information. Because of the complexity of moving mesh calculations of real size injectors, the nozzle flow is often studied at full needle lift only or by quasi-steady state fixed needle lift calculations, so that little is known about the transient phase of the needle opening/closing. The aim of this work is to evaluate this methodological approach, comparing predicted results obtained by simulations with fixed and moving mesh needle lift, and to characterize the cavitation process during the whole transient of the injection. The mathematical basis of the model and the numerical methodology followed are detailed in the paper. In fixed simulations, the needle was positioned at six different lifts, while in moving mesh simulations a range of 15µm to full needle lift was covered. By analyzing the acquired flow field images during the injection period, the highly transient nature of the flow was revealed. The moving mesh calculations provided a number of significant flow characteristics concerning the effects of the needle position in time. For instance, the effects of ascending and descending needle movement were noted by differences in the flow at identical needle lifts. Also observed, was the decrease of vapor and turbulence intensity at full lift, and clouds of vapor exiting the nozzle at certain times. Although the steady simulation captured the basic flow structure inside the hole at high and low lifts, it did not capture the time dependent flow characteristics mentioned above. The two provide different nozzle exit results for low needle lifts, while the percentage difference changes depending on the lift. Hence, the calculations with moving mesh boundaries provide information about the transient phase of injection that may not be neglected.*

1 INTRODUCTION

The nature of diesel injector internal flow is highly transient mainly affected by the needle movement. Experimental studies have revealed the importance that the opening and closing of the needle can have on the cavitation structure[1,2]. However, the complexity associated with the experimental determination of nozzle flow characteristics suggests investigation with CFD, as it represents a promising tool in predicting the three-dimensional flow inside the nozzle and how it affects the conditions at the nozzle exit. When considering the simulation of diesel injector internal flow, one must make the choice of either applying a time accurate transient moving mesh approach or a simplified "pseudo" steady state approach. This modeling decision can be critical for the prediction of nozzle exit conditions, especially when simulating a cavitating nozzle. The prediction of the nozzle exit conditions is of great importance as it provides insight into predicting the realistic spray characteristics.

Several studies predicting the effect of needle position on diesel internal flow in steady state regime have been presented in the last few years[3,4]. Additionally, studies have been performed with moving mesh calculations in an attempt to study the effect of the transient opening/closing of the needle valve on the injector internal flow[5,6,7]. The calculations allowed to identify the significant effect of the needle motion on the cavitation distribution and to observe complex phenomena like the formation of a swirling flow. Other studies performing moving mesh calculations were more focused on predicting the effect of internal flow on spray formation[8,9,10,11]. An increased number of studies have compared the effects of steady-state and transient boundary conditions on the nozzle exit results using fixed geometry domains[12,13]. However, hardly any attempts have been made in comparing results of fixed and moving mesh calculations in order to evaluate the methodological approach, being limited to comparative results of small number of constant needle positions[14] or to results related to the development of cavitation pattern[15].

This study will present predicted results obtained with fixed needle lift calculations and calculations in a transitory regime (moving mesh calculations). A full comparison of the predicted results in terms of cavitation, turbulence intensity and injection rates are given during the injection time. It should be noted that even the steady state calculations are time dependent due to the transience of the cavitation model. At fixed calculations the needle was positioned at 25, 50, 75, 100, 200, 250 μm, while in the moving mesh calculations a range from 15-250 μm was covered. The simulations were performed with a finite volume based commercial code[16].

The paper has the following outline: Section 2 describes the nozzle internal flow calculation method with fixed and moving mesh calculation. Section 3 deals with the comparison between the two calculation methods, giving results about the predicted nozzle internal flow. Some conclusion remarks are given in Section 4.

2 CFD APPROACH

In the following section, some details of the CFD approach for the fixed needle and moving mesh calculations are presented and discussed. The meshes of both kind of calculations were fine enough to give grid independent results and explanatory sketches of them are illustrated in Fig. 1. In the transient calculations, the 80.000 cell computational grid consisted of a non-moving part in the area of the injection hole and a moving part in the annulus between the needle and needle seat, which allows for the transient motion of the needle to be considered. The cells between the needle and nozzle body expand and contract with the corresponding needle movement. Taking advantage of the injector symmetry, a sixty degree sector was used for both kinds of calculations to mitigate the computational cost. Results of both cylindrical (cavitating) and conical (non cavitating) nozzles will be presented here. The operating conditions are representative of high pressure injection engines and are shown in Table 1.

A commercial code, which is based on a finite volume discretization was used to perform the calculations presented here; the governing equations can be found in reference[16]. Both the fixed and transient needle lift calculations presented here were made using the conventional k-ε turbulence model with hybrid near wall treatment. The solver is based on the pressure correction method and uses the SIMPLE algorithm. In terms of discretization the MARS scheme was used for the momentum equations and the upwind differencing scheme for the k-ε turbulence model equations.

The cavitation model was based on the Rayleigh equation, which links the rate of change of the bubble radius with the local pressure. In this model both the liquid and vapor densities are constant and there is no slip between bubbles and liquid. The liquid fuel density is 828 kg/m^3, its molecular viscosity 2.14×10^{-3} kg/ms, while the vapor density is 0.025 kg/m^3 and its molecular viscosity 1×10^{-5} kg/ms. The number of seed bubbles per unit volume of liquid is constant and is also a model parameter to be specified. In this study, the seed radius was set to 1.0×10^{-6} m and the nuclear number density to 1.0×10^{14} m^{-3} in agreement with values proposed in the literature for real-size nozzle simulations[17, 18]. More details about the configuration of the flow model can be found in reference[19].

P_{in} (bar)	800, 1500
P_{back} (bar)	10, 50
Needle lift (μm)	25, 50, 75, 100, 200, 250

Table 1: Fuel injection conditions.

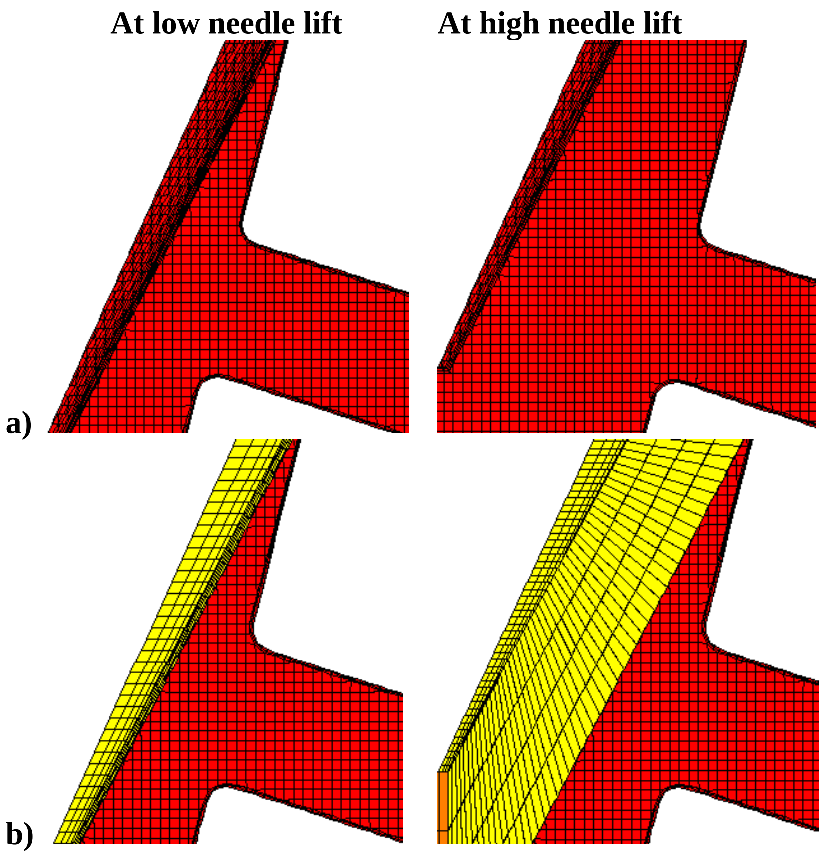

Fig. 1: Computational meshes at high and low lifts for a) fixed and b) moving needle lift calculations.

2.1 Fixed needle lifts simulations

With respect to the simulation method, quasi-steady state computations were performed for the entire range of fixed needle lifts; the needle was initially set at the smallest opening value (25 μm) and the unsteady calculation performed until the solution no longer evolved. For the remaining values of needle lift, the calculations were started from the previous lift solution (e.g. for 50 μm, the run was started from the solution obtained for 25 μm). The time step for these calculations was 1.0×10^{-6}. The injection rate of each calculation was obtained and used to assign the lift law to the needle movement in transient calculations, as will be detailed in the following section of the paper.

2.2 Moving mesh needle lifts simulations

In this series of calculations, the opening and closing of the needle valve was considered, and the evolution of the cavitation regime was simulated transiently. For the initial condition, the inside of the injector was filled with liquid (steady-state calculations with cavitation model not connected) to stabilize the flow during the first time steps. For numerical purposes, a minimum lift position for the needle had to be established, as a simulation with a completely closed needle cannot be realised, and moreover is physically meaningless. The selected minimum needle lift for both cases was set to 15 μm. The time step for the transient calculations was 50% less than the fixed needle cases in order to improve accuracy. More details about the configuration of the transient needle lift simulations, including the methodology of performing them, can be found in [20].

Since the needle lift law as a function of time is not known, and could not be measured, the following technique was followed to extract it. Six calculations were performed, each at a different needle lift, and the curve injection rate as a function of needle lift was obtained. A correspondence between this curve and the experimentally measured injection rate yields the needle lift law as a function of time (Fig. 2, a).The needle lift values that were used as input for the model are shown in Fig. 2, b alongside the calculated and experimental injection rates for 1500/50 bar.

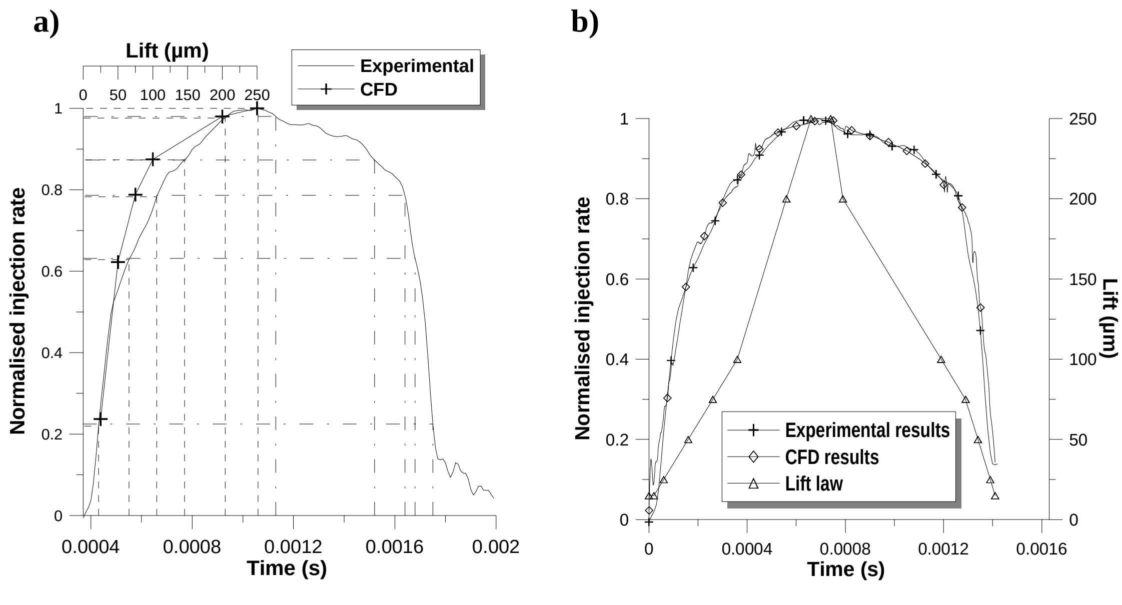

Fig. 2: a) Interpolation method used for estimating the lift law, b). Needle lift law and comparative experimental and calculated injection rate curves.

The small differences observed between the experimental and measured injection rates are due to the constraints of the interpolation made on the lift law. The plots are normalized using the highest value of the injection rate for both the experimental and computational results. Having described the methodological approach of fixed and transient needle lift simulations, the analysis results of both kinds of simulations is proceeded.

3 RESULTS AND DISCUSSION

3.1 Comparative Study of Internal Flow Distribution

It has been observed that the cavitation intensity depends strongly on the needle lift due to the effect of turbulence and vortices present in the nozzle hole. In Fig. 3 predicted TKE distributions with fixed and moving mesh calculations for the cylindrical nozzle are shown. At each lift the color scale is the same between both kind of calculations. It ought to be mentioned at this point that although a pseudo-steady condition is reached at the end of each fixed needle simulation there is a fluctuating behaviour in the flow distribution. It should be clarified that the presented images are part of a transient timeline, in which for some time instances the flow pattern becomes momentarily slightly different; for this reason the selected images are an averaged representation of the flow. As it is seen from the images the turbulence intensity appears mainly in the hole inlet and dissipates along the nozzle hole. The fixed needle calculations can predict the increased flow turbulence caused by the restricted passage of the flow in the region between needle seat and nozzle. At low needle lifts (< 100 μm), a kind of hysteresis between the needle valve opening and closing in the moving mesh calculations is clearly seen by the images. On contrary, at high needle lifts the difference of TKE between valve opening and closing decreases.

Similar comments can be given for the prediction of vapor distribution by the two methods. In Fig. 4 distributions of the predicted volume fraction of vapour is shown. As it is seen both calculation at certain lifts predict a swirling cavitating flow which propagates up to the nozzle exit. The moving mesh calculations predict that the cavitation development is more pronounced at needle closing, while the field of fixed needle calculations are closer to those at needle opening. The fixed lift calculations appear similar to the predicted distributions of the moving mesh calculations at high lifts due to the decrease in transience. However, the fixed needle lift calculation could predict the secondary vortex structure at low needle lifts and the more stable cavitation structure at high needle lifts as it is seen in Fig. 4. But the advantage of the moving mesh calculations is that can provide aditional information concerning whether the enhanced quantity of vapor is found in the ascending or descending needle movement.

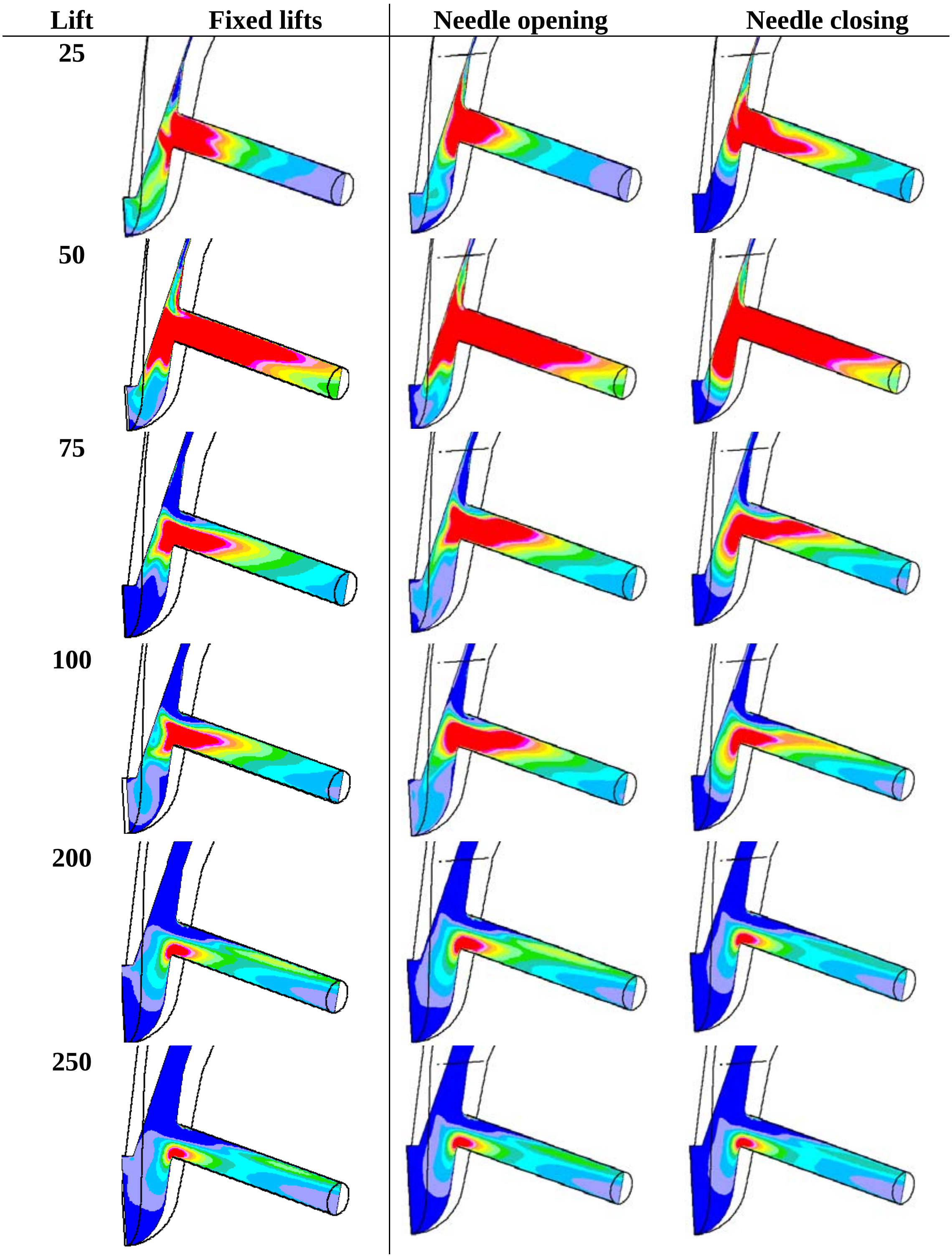

Fig. 3: Comparative view of TKE (m^2/s^2) at different needle lifts for fixed and transient needle lift analyses, 1500/50 bar. (the same color scale at both calculation methods of each lift is used).

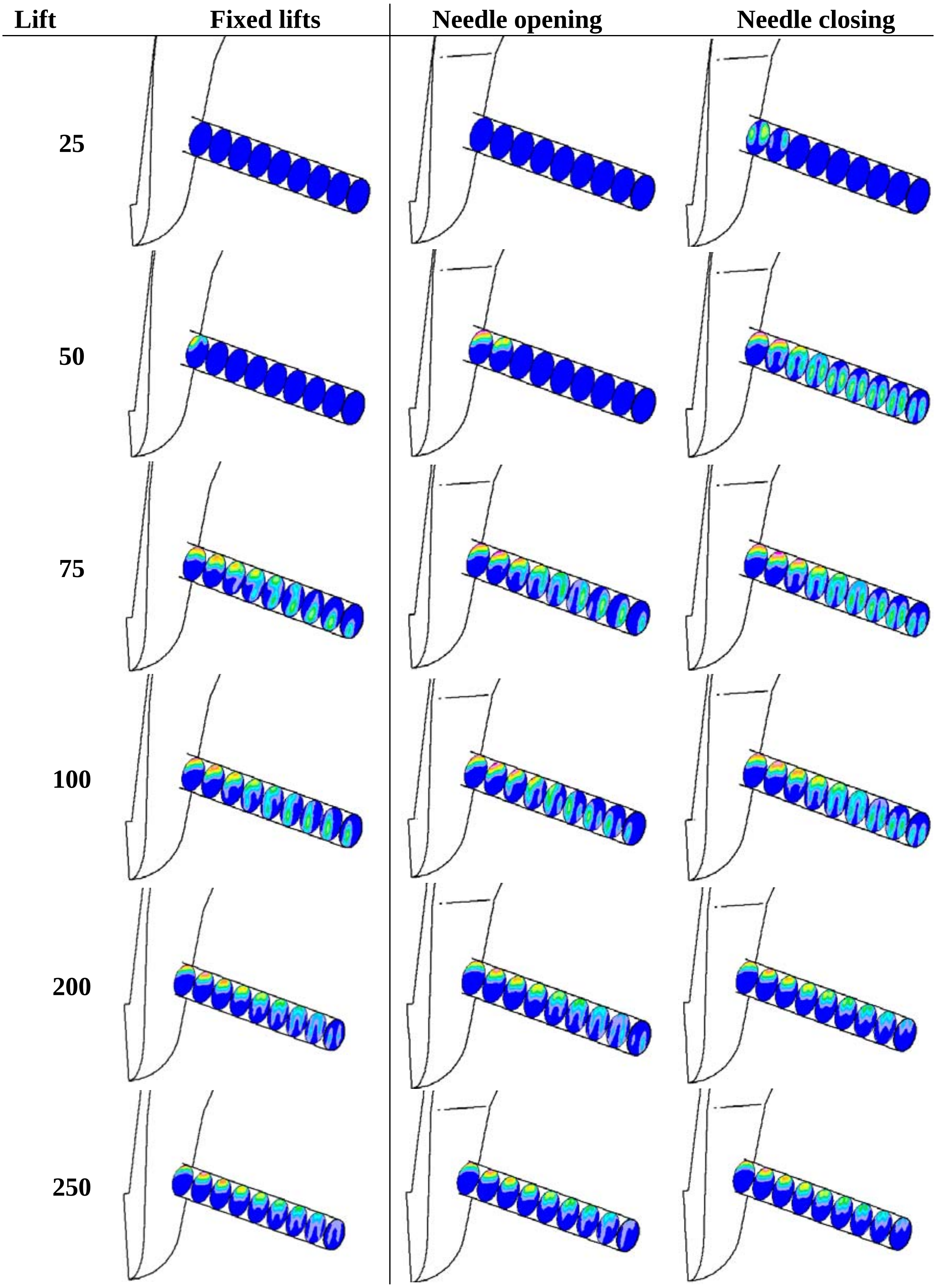

Fig. 4: Comparative view of volume fraction of vapor at different needle lifts for fixed and transient needle lift analyses, 1500/50 bar (color scale: 0-1).

3.2 Comparative Study of Nozzle Exit Characteristics

Concentrating now on the nozzle exit, the effect that the cavitation pattern has on the outlet flow conditions with both kind of calculations is analysed. In Fig. 5 the temporal variation of the cavitation intensity is demonstrated by plotting the area averaged volume fraction of vapour and turbulence intensity at the exit of the nozzle (1500/50 bar). The instantaneous evolution of the moving mesh calculated values shows the highly transient nature of the flow, raising the question of whether fixed needle lift simulations can accurately predict the effect of the opening and closing phase of the moving mesh calculations on the cavitation intensity.

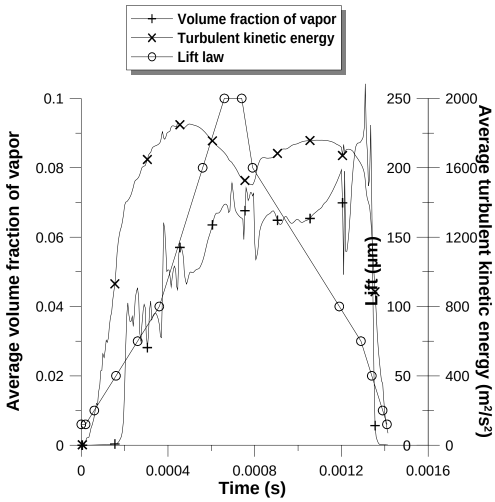

Fig. 5: Lift curve, average instantaneous TKE and volume fraction of vapor at the exit of the nozzle (1500/50 bar).

As can be seen in Fig. 5, a kind of hysteresis is observed between the needle valve opening and closing for volume fraction of vapour and TKE instantaneous values. Overall, more vapour reaches the nozzle exit during needle closing than during needle opening. Contrarily, the turbulence intensity reaches higher levels during the nozzle opening. Althouh the turbulent dissipates along the nozzle, as it was mentioned above, its efect is still noticeble at the nozzle exit. It is worthwhile to note that calculations were performed at different operating conditions, with different nozzle shapes (conical-cylindrical), different nozzle types (single-hole, six-hole nozzles) and different lift curves. The phenomenon of hysteresis was present in all cases.

Another characteristic of the flow that was observed was an increase in cavitation intensity at low lifts when the needle closes (Fig. 5). This can be explained by the fact that at certain times the cavitation cloud grows and exits from the nozzle. When it grows all the area is occupied by vapour, but just seconds later the area is occupied by only liquid as the vapour cloud has been evacuated. Similar observations detecting an increase in the cavitation intensity when the needle starts to close have been published in[21]. However, at low needle lifts, the fixed calculations did not show similar clouds exiting the nozzle.

Additionally, as seen in Fig. 5, a slight decrease in cavitation intensity is observed when the needle is fully open. Similar observations can be found in references[22,23]. This effect is attributed to the simultaneous pressure fluctuations in the inlet and outlet of the nozzle. The results of the fixed needle calculations are close to the transient values, but are not able to capture the decrease in vapour as will be illustrated below.

An attempt was made to quantify the difference of the cavitation and turbulence results obtained by the two methodological approaches at certain lifts. In Fig. 6, the values of TKE at the exit of the nozzle of the moving mesh calculations are compared with the time average values of the fixed calculations. Results of both nozzles (conical/ cylindrical) and two operating conditions (800/50 bar, 1500/50 bar) were selected to be presented here in order to see the effect of geometry and injection pressure. The opening/closing results of the moving mesh calculations have different tendencies for low and high lifts. For low lifts the needle closing values are considerably higher than the other calculations, while for higher lifts (above 100 μm approximately) the needle opening values are higher. This difference between opening and closing values increases when the pressure drop increases. Additionally, the difference is enhanced from medium to high lifts (100 a 200 μm). The results for the fixed lift calculation are between the needle opening and the needle closing as if they were average values. At full lift, the difference between the opening and closing values tends to decrease. These observations seem to be independent of the nozzle geometry, as the conical geometry (non cavitating nozzle) have showed similar tendencies.

However, the values predicted by the fixed needle at the outlet qualitatively match with the moving mesh results. The results of both approaches clearly show that the TKE values significantly increase with increasing needle lift until a certain value. Afterwards, it is less sensitive to further lift increase. The turbulence level at high lifts depends on the injection pressure and is approximately double for the 1500 bar cases. The results also show that there is a drop in turbulence level at full lift when the needle opens. This drop can continue during needle closing as seen by the moving mesh results. The fixed needle results cannot capture this phenomenon because the TKE is always higher at 200 μm when compared to 250 μm.

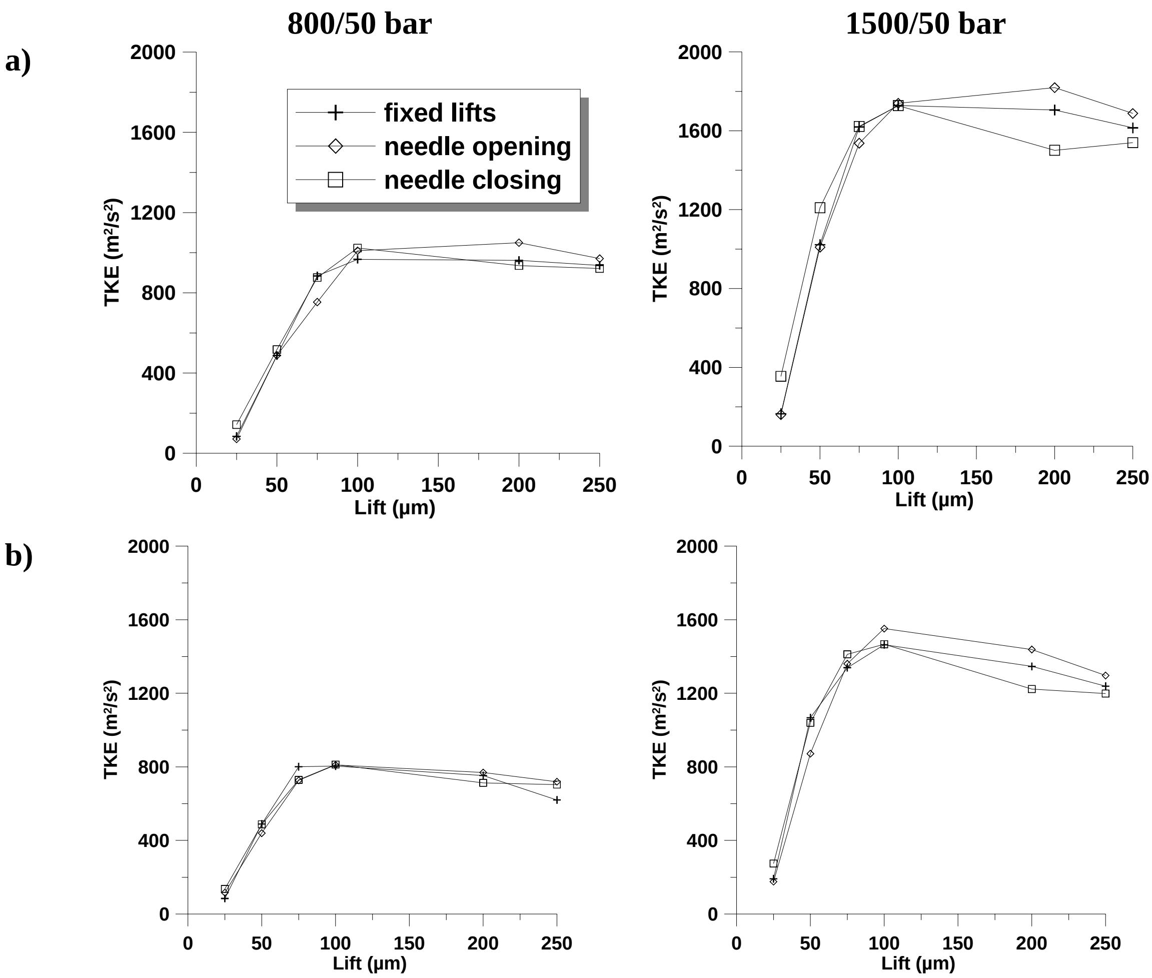

Fig. 6: TKE at different lifts with fixed and moving mesh calculations at 800/50 and 1500/50 bar for a) cylindrical and b) conical nozzle.

Fig. 7 presents the percentage of area occupied by vapour at the exit of the nozzle as a function of lift for both the fixed and moving mesh calculations for four different operating conditions. The area of all cells containing at least 5% of vapour is represented. Only the results from the cylindrical (cavitating) nozzle are presented. The aim is to see if the deviation of mean vapour volume fraction values from the fixed calculations approaches the values from the moving mesh calculations (opening/closing). As mentioned above, although the needle is fixed, the modelling of the cavitation phenomena itself is transient. Therefore, there is a deviation of the mean value of volume fraction of vapor. It can be claimed that the fixed needle lift calculations do not reasonably predict the transient behaviour of the phenomenon inside the injection hole at all lifts. No clear trend can be observed with respect to the ability of the fixed calculations to approach the results of transient calculations. The standard deviation of the volume fraction of vapour is increased for the lifts in which the vortex structure propagates downstream from the hole entrance to exit. Overall, at low lifts the vapour generated by the fixed mesh tends to be closer in value to that of the needle opening; the model seems unable to capture the high level of generated vapour at low lifts. Contrarily, at full lifts, the generated vapour of fixed calculations is higher.

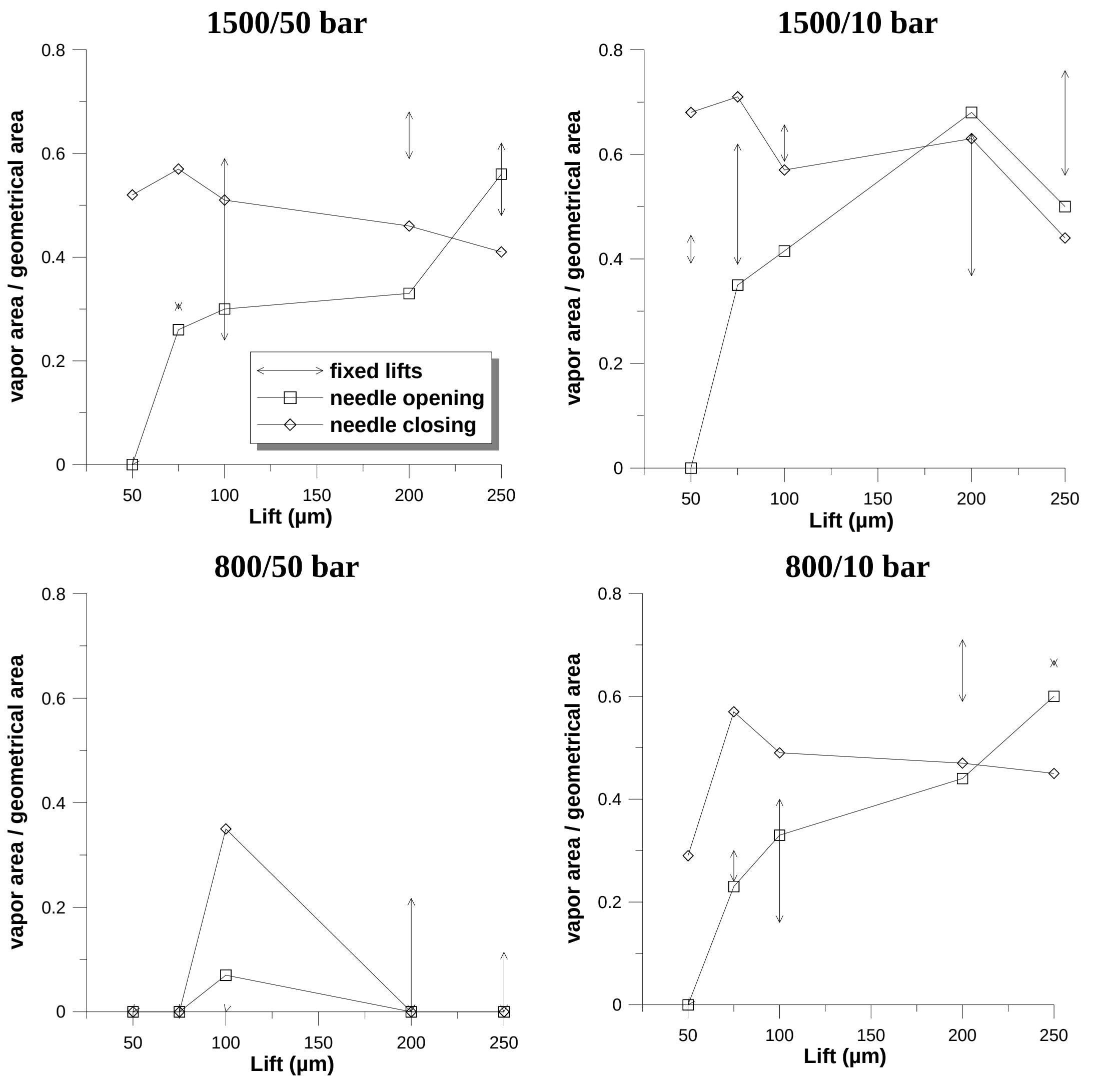

Fig. 7: Percentage of area occupied by vapor at the nozzle exit as a function of lift with fixed and moving mesh calculations for different operating conditions.

In Fig. 8 the comparative injection rate of fixed and moving mesh calculations is presented. From this comparison it can be argued that although cavitation intensities can be different as previously mentioned the injection rates remain quite close. This tendency was also observed in reference [14].

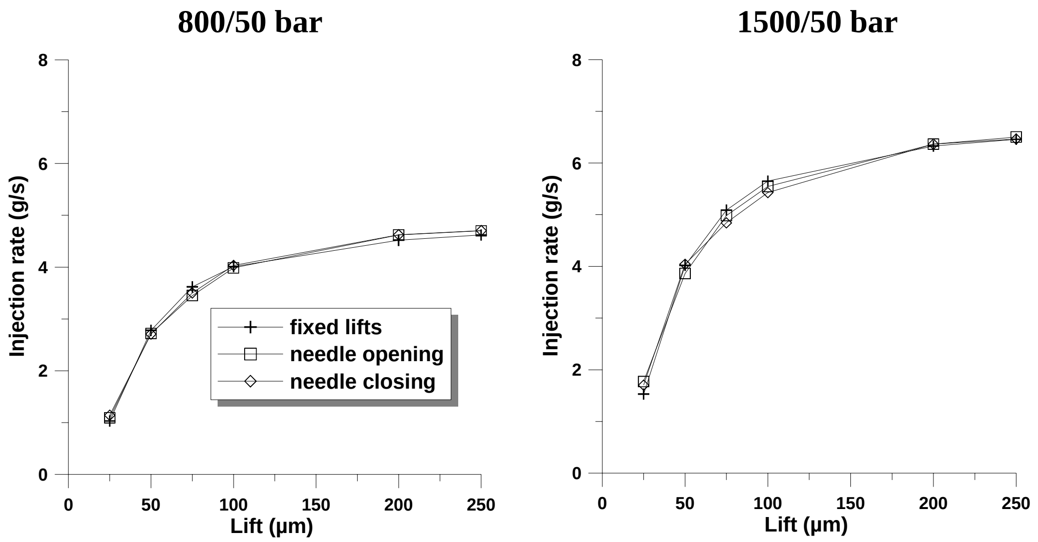

Fig. 8: Injection rate at different lifts with fixed and moving mesh calculations at 800/50 and 1500/50 bar for cylindrical nozzle

4 CONCLUSIONS

The effect of a moving needle on injector flow structure is studied with fixed needle lift and moving mesh simulations. The conclusions of the comparative results of the two methodological approaches are presented.

- The fixed needle simulations, concerning the TKE intensity, provided some basic flow characteristics such as the enhanced turbulence in the nozzle hole and the decrease of turbulence intensity at full lift. Besides, captured the nature of the nozzle hole cavitation phenomenon at high and low needle lifts. At low lifts, the simulations qualitatively predicted the vortex flow and the unsteady nature of cavitating flow. At high needle lifts, a more stable cavitation pattern attached mainly to the upper part of the nozzle was predicted. In addition, the injection rate comparison with the moving mesh calculations showed a strong correlation for all lifts.

- The transient moving mesh analysis additionally provided a number of flow characteristics concerning the effects of the needle position in time. Specifically, the results of transient analysis captured the hysteresis of vapor formation and turbulence intensity, the decrease of vapor at full lift and peaks of vapor formation at certain times. From the above it is deduced that is very important to take into account the transient phase of injection.

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