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INVESTIGATION ON SPRAY CHARACTERISTICS UNDER ULTRA-HIGH INJECTION PRESSURE CONDITIONS

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ABSTRACT−This article reports the experimental and numerical results for free sprays under ultra-high injection pressure conditions to give us better understandings of spray characteristics and also to make clear a limit pressure condition in diesel sprays. The high pressure injection system developed in this work is devised to reach ultra-high pressure conditions in the range from 150 MPa to 355 MPa. The free spray injected from a single nozzle injector is visualized by the Schlieren technique and the high speed camera. In particular, it is found that the shock waves are present and propagated along the edge of spray in the downstream direction. The measured spray penetration length increases gradually with the injection pressure, but its increasing rate is decreased as the injection pressure increases. The Sauter mean diameter is also no longer augmented for the injection pressures higher than 300 MPa. In addition, the three-dimensional numerical simulations are conducted for comparing the measurements with the predictions based on two different breakup models. The TAB model results show better agreements with experimental data than the WAVE model under ultra-high injection pressure conductions. Moreover, the simulation results show that the gas-phase pressure increases substantially in the vicinity of the spray tip region. It supports the experimental observation that the shock waves are formed at the front of spray tip and are propagated downstream.

KEY WORDS : Ultra-high injection pressure, Spray penetration, Diesel engine, Atomization, Shock wave

1. INTRODUCTION

Enhancing performance and reducing the pollutant have been one of the important issues encountered in high technologies of diesel engines (Reams and Wiemero, 1982; Racine and Miettaux, 1991). As efforts to promote the mixing of fuel with air, a number of researches have been performed persistently by using the high injection pressure systems (Kobayashi, 1992; Yokota, 1991; Jang *et al.*, 1996; Jeong *et al.*, 1998). Since the air-fuel mixture formation is highly affected by various injection conditions, however, the extensive studies need to be performed for providing better understandings of spray characteristics.

Some researchers (Jang *et al.*, 1996; Jeong *et al.*, 1998) investigated a novel system with the injection pressures in the range from 100 to 200 MPa to enhance the atomization. Consequently, it was found that this enhancement of atomization reduced the emission such as Nox, HC, and soot. Jeong *et al.* (1998) constructed a combustion system for studying spray dynamics under ultra-high injection pressure conditions. They indicated that there might be a critical injection pressure above which injected sprays would be no longer atomized. Song *et al.* (1997) provided the information for the diesel spray characteristics by using PMAS in the range of injection pressure below 14 MPa.

For the injection pressure higher than 150 MPa typically, the shock waves are present near the spray tips and they may be strongly interacted with injected droplets. Ranger and Nicholls (1969) investigated the drop breakups by shock waves. Nakahira *et al.* (1992) visualized the spray development using the Schlieren technique and measured the tip penetration lengths and the SMDs at different injection pressures raised to 250 MPa maximum. It was observed that the weak shock wave occurring at the spray tip propagated along the outmost surface of spray in the downstream direction. They also argued that the shock waves would exist in real engines for injection pressures larger than about 180 MPa. MacPhee *et al.* (2002) reported that there were different phenomena from earlier observations through their visualization results using a synchrotron x-radiography and fast x-ray detector at 50 and 135 MPa. They

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**Corresponding author.* e-mail: cfdmec@cau.ac.kr found that the shock waves were captured at the spray tips and their reflected waves were propagated downstream with time. Although the shock waves was assured to occur near the edges of spray from several experimental results as referred, the effects of shock waves on atomization have still remained controversial. As a matter of fact, because most of research reported earlier have been carried out under the injection pressure lower than 150 MPa, the more detailed information on spray characteristics under much higher injection pressure condition are required.

One of the most efficient ways to analyze the spray characteristics has been in use of several numerical submodels for atomization and secondary breakup such as the WAVE model by Reitz (1987), the Taylor Analogy Breakup (TAB) model (1987), and the drop drag model (DDB) of Liu *et al.* (1993). Even these models widely used in most of diesel engine simulations involve no information on the droplet interactions when the shock waves are present, because nobody knows clearly what happens under the ultra-high injection pressure situations. For analyzing this interaction between shock waves and injected sprays, it is necessary to obtain the sufficient experimental data from the fundamental experiment on a single droplet/shock waves interactions. Based on these efforts, the reasonable theory should be proposed. As a first step toward doing this, it seems to be useful to examine whether the previous models are suitable for the case that shock waves exist. This effort would be helpful in developing a numerical model for atomization and injection conditions.

Thus, the ultimate goal of the present study is to investigate the spray characteristics by measuring some important parameters, i.e., spray tip penetrations, spray volumes, and entrained air masses, and by visualizing spray patterns. The injection pressure ranges from 150 to 355 MPa. We also simulate the free sprays injected from the nozzle under the ultra-high injection pressure condition, and compare the predicted results with the measured data.

2. EXPERIMENTAL APPARATUS

Figure 1 is an experimental apparatus that consists of the ultra-high injection system, spray visualization equipment, control system, and DAQ (data acquisition) hardware. As seen in Figire 2, the ultra-high injection system includes the first compression unit, the second compression unit where the fuel is pressurized by plunger pump, the cylinder-type stopper, and the recoverring unit allowing the cylinder for operating plunger to be returned at the original state. For reaching ultra-high injection pressure, the fuel should be compressed initially by the additional booster pump. The pressurized fuel enters the plunger pump in which the pressure of fuel rises rapidly through the hydraulic cylinder. The stopper is utilized in controlling the cylinder for driving plunger as rapidly as possible. This control unit allows the injection pressure to raise up to about 400 MPa. The self-fabricated high-pressure injector is the DLL-S type of single injection with the diameter of 0.2 mm. It can be seen from Figure 1 that the visualization equipment used in the present study includes the high-speed drum camera (Cordin 350) with maximum of 35,000 frames per second, its control unit, and Ar-ion laser of 5 W as the light source. In order to visualize both the pressure waves and the spray shapes effectively, we adopt the schlieren technique with the concave-type mirrors of 300 mm diameter. The following ways are taken for visualization in this study. At first, the moving signal of hydraulic cylinder rod can be taken with the photo sensor. The signal can be then delayed by using the pulse/delay generator (BNC, model 555). This signal

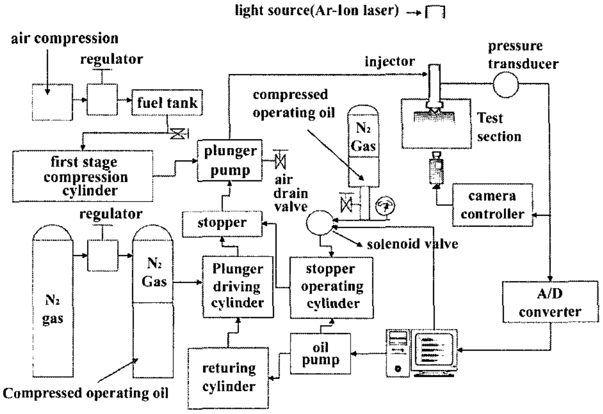


Figure 1. Block diagram of experimental apparatus.

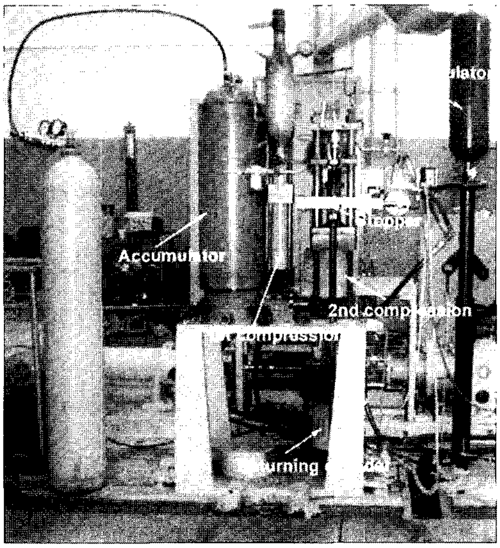


Figure 2. Photograph of modified UHPIE.

is sent out to the drum camera before the plunger pump is compressed by the hydraulic cylinder rod. Just prior to beginning of injection, the shutter of drum camera is opened and the overall shapes of sprays can be captured by the drum camera. The injection pressure considered in the present work ranges from 150 MPa to 355 MPa to examine the influence of injection pressures on spray penetration lengths, spray volumes, and Sauter mean diameters. In particular, the droplet sizes are measured by PDPA at 60 and 120 mm downstream from the nozzle exit.

3. NUMERICAL STUDY

The main goal of the present numerical simulation is to compare the experimental data with the predictions using different atomization models. The simulation code is the extended version of EPISO code (Lee and Ryou (2001)). This effort is needed because most of atomization models have been evaluated for relatively low injection pressure conditions. It is thus necessary to examine whether the earlier atomization models are suitable at the condition of ultra-high injection pressure. In other words, our interest is mainly concentrated on whether the earlier atomization models can show good agreements with the experimental data in spray characteristics, even under the situations with ultra-high injection pressures. We adopt two representative models such as the WAVE model of Reitz (1987) and the TAB model of O'Rourke (1981), widely used for nearly past two decades. In the TAB model, the critical Weber number is assumed to be 6.0. The empirical constants C_d, C_b, C_k, and C_F are taken as 5.0, 8.0, 1/3, and 1/2, respectively to match the experimental data with predictions (O'Rourke and Amsden (1987)). For a mimic of the droplet/droplet collision and coalescence, the model of O'Rourke (1981), one of the most famous models published earlier, is used in the present study.

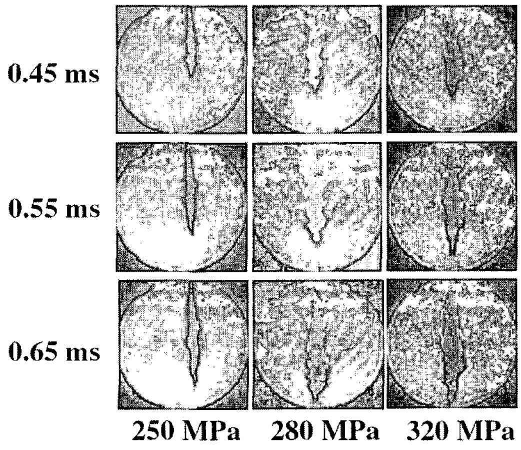


Figure 3. Flaming photographs of shock wave generation at the tip of fuel spray.

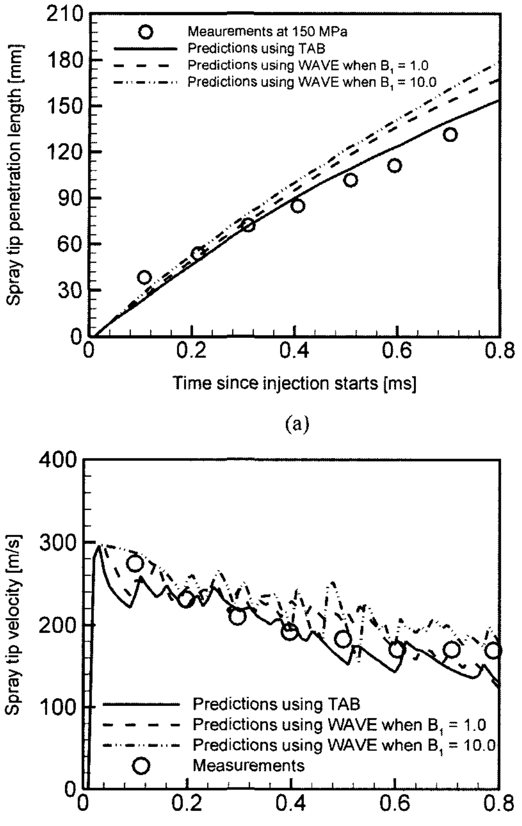
The three-dimensional numerical simulations are conducted for gas and dropet phases involving the compressibility effects. In contrast with the gas phase, the liquid phase is calculated by the ordinary differential equation based on Euler's implicit method. The present code used for calculating the spray dynamics have been continuously validated by comparing predictions for various test cases with experimental data (Lee and Ryou (2000, 2001), Lee *et al.* (2000)). The free sprays are simulated at three different injection pressures of 150, 250, and 320 MPa. The gas pressure is 0.1 MPa.

Computation domain for all cases consists of $52 \times 52 \times 52$ (x, y, and z respectively) grids which is determined from several grid independent tests, previously. A time step of 2 μs is adopted and the total number of 4000 droplet parcels is introduced through an injection duration time. The predicted results of the WAVE model and the TAB model are compared with experimental data for spray tip penetration lengths, tip velocities, and Sauter mean diameters.

4. RESULTS AND DISCUSSION

Figure 3 represents the transient behavior of free sprays at different injection pressures. As the injection pressure increases, the dispersion of droplets increases in the axial and radial directions. At the injection pressure higher than 350 MPa, the nearly same trends are observed. When the injection pressure is higher than 280 MPa, such wiggling and wavy patterns are found near the edge of spray. It indicates that these patterns seem to be shock waves propagating downstream along the edge of spray. Before the wavy patterns are referred, we should pay our attention to the feasibility of existence of shock waves. This shock wave occurs because the tip velocities become larger than the speed of sound, and the corresponding Mach number is higher than unity at the early stage of injection start. The spray tip velocities rapidly decrease due to the aerodynamic resistance, whereas the shock wave speed becomes nearly constant as it propagates downstream. Once the pressure wave is formed near the nozzle exit, therefore, the wave speed becomes higher than the speed of spray tip. It is not obvious even until now how the shock wave affects the atomization process. More elaborate studies are thus needed for better understandings of the shock wave/droplet interaction.

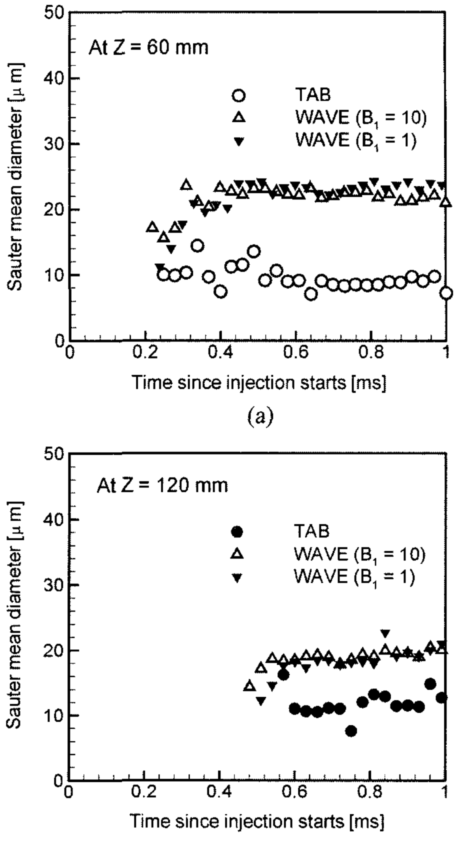
Figure 4 compares the tip penetration lengths and the tip velocities predicted by the WAVE model and the TAB model with the measurements at $P_{\mathrm{INJ}} = 150$ MPa. The tip penetration lengths predicted by the TAB model show fairly good agreements with experimental data, except for slight deviation appearing at the early stage of injection start. Unlike this, the WAVE model over-predicted



(a)

(b)

Figure 4. The measurements and predictions (a) for the spray tip penetration length and (b) for the tip velocities at $P_{\mathrm{INJ}} = 150$ MPa.



(a)

(b)

Figure 5. The SMD predictions at $z = 60$ and 120 mm for $P_{\mathrm{INJ}} = 150$ MPa.

the spray tip penetration lengths substantially and the deviations from experimental data gradually increase as time goes on. We investigated the influence of breakup time constant B_1 on tip penetration lengths. As would be expected, the tip penetration lengths increase slightly as the breakup time constant B_1 increases, indicating that the increase of B_1 provides larger droplets after atomization in the WAVE model. In spite of the existence of slight deviation after $t = 0.14$ ms, the TAB model is in better agreements with experimental data than the WAVE model. For $t < 0.12$ ms, the predictions of TAB model are nearly same as those of the WAVE model at $B_1 = 1.0$. It means that the breakup time constant $B_1 = 10$ used by Reitz (1987) seems to be inappropriate for the ultra-high injection pressure.

In predicting the spray tip velocity, both models are qualitatively in good agreements with experimental data. The spray tip velocities decrease rapidly at the early stage of injection start because the droplets injected just from the nozzle exit experience the largest resistance against gas flows due to the highest relative velocities between droplet and gas phases at the earliest stage of injection start. Even at 150 MPa, the spray tip velocity reaches nearly the speed of sound. It supports that the wiggling and wavy patterns observed in Figure 3 are feasible to be shock waves formed near the nozzle exit at the early stage of injection start and propagated in the downstream direction. Figure 5 presents the transient behaviors of SMDs predicted by the WAVE model and the TAB model at $z = 60$ and 120 mm from the nozzle exit when $P_{\mathrm{INJ}} = 150$ MPa. The WAVE model yields much larger droplets at two different locations than the TAB model and also its results rarely depends on choosing the breakup time constant.

In fact, the WAVE model intrinsically produces larger droplets than the TAB model. One of the major reasons behind this difference is found in different mechanisms on which both models are based. Basically, the WAVE model considers the linear instability of infinitesimal waves on an axially symmetric jet surface of infinite length and assumes the jet flows to be incompressible. Contrary to the WAVE model, the TAB model does not assume the incompressible flows basically and mainly

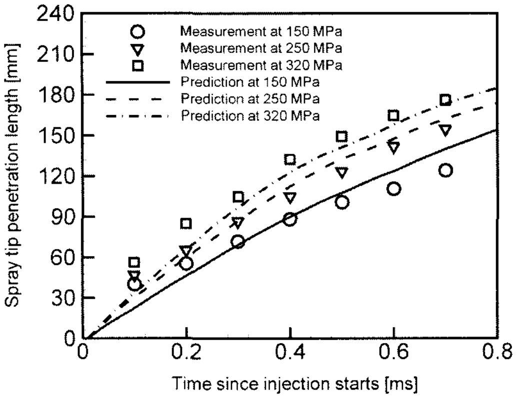


Figure 6. Comparisons of the spray tip penetration lengths predicted by the TAB model with the experimental data in the present study.

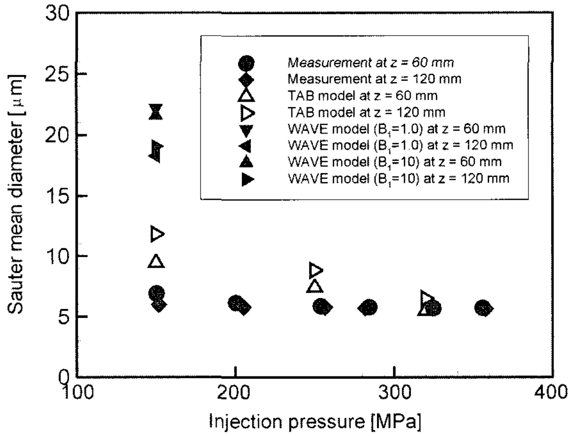
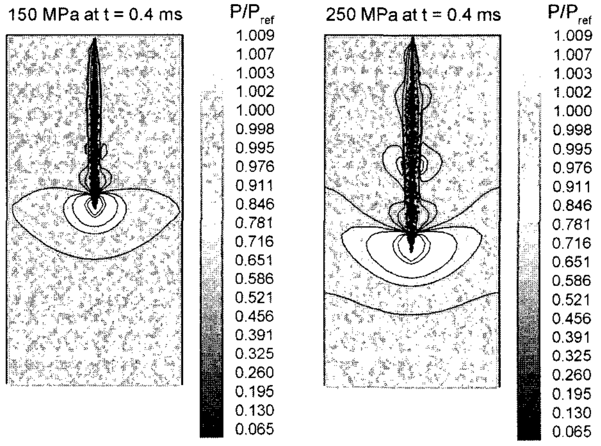


Figure 7. Comparisons of the averaged SMDs at different locations with the experimental data.

consider the deformation of droplet itself which satisfies the energy conservation law. Nakahira *et al.* (1992) observed the existence of weak shock waves which are driven by the sprays reaching the sound velocity in the vicinity of spray tip. According to their observations, it can be stated clearly that the gas phase flows be no longer incompressible in real situation when the injection pressure is extremely high. If the shock wave exists in the flow fields, the rapid pressure rise due to the shock wave can play an important role in directly distorting and deforming the droplet after breakup in the normal direction to the path of the parent droplet. Hence, the WAVE model can be inappropriate in simulating the diesel sprays with very high injection velocities, especially higher than the sound speed at the given temperature. Unlike this, the TAB model seems to have more appropriate mechanism in describing a direct interaction between droplets and high velocity flows. However, none of other experimental and theoretical works have suggested a range of injection pressure above which the WAVE model would be inappropriate. We thus remain a knotty subject to be solved as future works in determining this range of injection pressure. In what follows, the influence of injection pressure on atomization and flow characteristics will be discussed and also the results simulated by the TAB model are only presented because the WAVE model shows the considerable deviations from the experimental data as indicated previously.



(a) $P_{\mathrm{INJ}} = 150$ MPa (b) $P_{\mathrm{INJ}} = 250$ MPa

Figure 8. The predicted non-dimensional static pressures at $t = 0.4$ ms for different injection pressures.

Figure 6 presents the spray tip penetration length with time at different injection pressures. These lengths gradually have increasing tendencies with time for most of injection pressure conditions. Generally, the TAB model shows good predictions in the tip length of fuel spray, compared with the experimental data in the range from 150 MPa to 320 MPa.

The averaged SMDs at 60 mm downstream shown in Figure 7 are obtained by numerically averaging the predicted SMDs during the total calculation time at different injection pressures. The droplet sizes decreases slightly with increasing injection pressure because of the increase of relative velocities between droplets and gas flows. However, after 280 MPa, the droplet sizes do not vary with injection pressure any more and approach to such a constant value, 10 micron. This shows a possibility that there are like to be such a injection pressure limit for mixture of gas with fuel. What the droplet sizes appear to be constant is due to the fact that the droplets in the downstream region are collided with those in the upstream region. From the results at $P_{\mathrm{INJ}} =$ 150 MPa, it can be seen that the WAVE model overpredicts significantly the averaged SMDs compared to the TAB model. Contrary to the WAVE model, the TAB model agree well with experimental data, and it yields the best predictions in SMDs at $P_{INJ} = 320$ MPa. Additionally, the difference of predictions at two locations decreases gradually with increasing injection pressure. It is thus concluded that under ultra-high injection pressure conditions, the TAB model is more appropriate in simulating the spray characteristics than the WAVE model.

The contours of pressure ratio are presented in Figure 8 at $t = 0.4$ ms for different injection pressures, together with the spray patterns. The pressure ratio is defined as the ratio of the local pressure to the reference pressure. All cases show the increase of static pressure near the spray tip region. In particular, the isobaric lines are seen to be concentrated in some regions and the sheets of shock waves are shown more clearly in Figure 8(b) at the boundaries between the high and low pressure regions. In addition, it can be seen that the higher does the injection pressures and the broader becomes the high pressure region. Furthermore, the high and low pressure zones appear repeatedly along the spray axis. The static pressures around the spray are also highly perturbed along the spray axis. Along the centerline of spray in the downstream direction, rapid pressure jump is obviously found near the spray tip and its magnitude increases with injection pressure. The pressure ratios are less then unity mostly, except in the spray tip region. It means that the droplet velocities are accelerated much more than those at the spray tip. Additionally, this local pressure rise supports the feasibility that the shock waves may exist for a very high injection pressure, as consistent with the previous observations (Jeong *et al.*, 2002; Nakahira *et al.*, 1992; MacPhee *et al.*, 2002).

5. CONCLUSIONS

The extensive experiments and numerical simulations were conducted to investigate the spray characteristics under the ultra-high injection pressure conditions. The WAVE model and the TAB model for breakup are compared with relevant experimental data and also discussed on differences in predicting atomization of sprays. The results in the present study are summarized as follows:

For injection pressures higher than 280 MPa, the wiggling and wavy patterns were found around the spray edge. It confirms that the shock waves are formed at the vicinity of the nozzle exit and they propagate in the downstream direction along the edge of spray.

The higher becomes the injection pressure and the smaller does the secondary droplets. However, for higher than 280 MPa, the droplet size is no longer reduced and has such a limited value.

The TAB model is in better agreements with experimental data in predicting the spray characteristics than the WAVE model. For ultra-high injection pressures, the WAVE model under-predicts the atomization of droplets owing to its basic mechanism.

The substantial increase of static pressure is observed near the spray tip region, supporting the feasibility that there exists the weak shock wave. The static pressures around the spray are considerably perturbed along the spray axis.

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