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NUMERICAL STUDY ON THE EFFECTS OF CONTROL VALVE LEAKAGE ON CR INJECTOR PERFORMANCE

The paper presents the results of numerical investigation of the effects of the control valve leakage on the performance of Common Rail (CR) injector. A numerical model of a CR injector 1-st generation was developed in AVL BOOST Hydsim environment to achieve the research tasks. It is revealed that the control valve leakage has the biggest effect on pressure changing behaviour in the control chamber and, in turn, on the amount of fuel injected per cycle. The amount of fuel injected increases with the increase in the control valve leakage. The effect of the control valve leakage is higher the higher rail pressure and the shorter the duration of fuel injection. Pressure in the control chamber drops dawn to the minimum value earlier after the start of opening the control valve and rises to the maximum value later in the cycle when the control valve closes the outlet orifice as the fuel leakage from the control chamber increases. When the control valve leakage increases, the nozzle needle-valve rises earlier and descends back to the seat later in the cycle.

Keywords: common rail, fuel injector, numerical simulation, ball valve, leakage, diesel engine.

INTRODUCTION

As the requirements for vehicle fuel economy and exhaust emissions limits increase, the vehicle must meet more stringent test procedures throughout its service life. The performance of the fuel injection equipment largely determines the quality of the operation process of a diesel engine. Modern cars are most often equipped with the common rail (CR) fuel systems in which the opening of the injectors controls a solenoid valve. The movement speed of the injector nozzle needle depends on the alteration speed of the fuel pressure in the control chamber. The rate of change of fuel pressure in the control chamber is a function of the difference in flow rates at the inlet and outlet, which depends on the cross-sectional area of the outlet throttle opened by the control valve. During operation, the sealing surface of the control valve is subjected to high-frequency impact loads. In addition, fuel escaping through an open valve causes hydro-erosion wear. These factors change the geometric parameters of the surfaces of the control valve elements - the sealing ball and the seat - which affects the travel of the valve and, at the same time, the amount of fuel injected [1]. Therefore, even small changes in the control valve operation may significantly affect the fuel amount injected, especially when using pre-injection and idling modes. This change may occur because the stroke of the valve is only a few tens of micrometres. The control valves are also exposed to cavitation wear. The consequence of this phenomenon is deterioration in the injector leak tightness, which with the fuel being under high pressure causes excessive flow through the overflow port of the injector. Such types of damage result in a difficult starting of the engine and uneven idling [2]. Thus, the injectors play an important role in the obtainment of pre-assumed parameters of combustion engine operation.

A significant number of engine failures occur due to fuel injector malfunctions. Common rail diesel injection systems are highly sensitive to changes in fuel properties [3], so the increasing use of alternative fuels with different properties can also affect the durability of the entire injection system, including the injector. Z.Chomik and P.Lagowski analyzed the influence of fuel quality on the wear of selected elements of the common rail system [4]. The researchers provided visual inspection and verification of individual elements of 122 injectors made by Bosch, Delphi, Denso, and Siemens. Analysis of the results indicates that corrosion is a significant factor affecting the failure rate of the CR systems. The most common type of damage to injectors of this type is: 34% needle valve, followed by 31% nozzles, 29% control valves in the third place, 4% solenoid valves, and 2% others. CR injectors can be precisely controlled and tested on the test bench under laboratory conditions, whereas in "field conditions" their diagnosis is practically limited to measuring the volume of fuel flowing out of the control chamber of individual injectors or from all the injectors at the same time [5]. The measured fuel flow includes not only the fuel flowing through the control valve. The fuel flow also includes the leakages passing through the gaps between the control valve and its seat as well as between the injector needle and the body.

Not only experimental but also theoretical methods are widely used today to study the characteristics of the injection. For this purpose, numerical models of injectors with the real dimensions are created, and simulations are carried out. The simulated diesel injection systems are characterized by complex dynamic and hydromechanical processes [6]. Mathematical modelling and simulation of the fuel injection process provide an opportunity to select flexibly and easily various parameters and to evaluate their impact on fuel injection characteristics [7]. In addition, simulation makes it possible to estimate those parameters of the internal elements of the system that are very difficult or even impossible to measure experimentally. A common-rail injector model employs three sub-models (electrical, hydraulic, and mechanical) to describe all the phenomena that govern injector operation. An accurate fluid dynamic part is also a key factor of CR injector modelling. Many research groups continue active work on modelling the common rail injector operation conditions [8,9,10]. The researchers Caika and Sampl developed a common rail injector model based on the 1D fluid flow and multi-body dynamics approach in BOOST HYDSIM, including numerous hydraulic, mechanical, and electrical components [11]. Payri et al. [12] developed a model in the AMESim environment and suggest silicone moulds as an interesting tool for characterising the geometry of valve and nozzle hole. At first, it is essential to validate the potentials of all the sub-models before starting to use the model for estimating the effects made on the system performance by adjustments or geometrical modifications. Most of the studies conducted aiming to optimize common rail injector construction parameters and their influence on the injection performance.

The purpose of the study is to examine the effects of leakages in the control valve of the injector on the amount of fuel injected and other operating parameters of the injector.

RESEARCH METHODOLOGY

The AVL BOOST Hydsim integrated platform for 1D system simulation was used to perform the modelling. Within this environment, a set of validated libraries was also used, containing pre-defined components for different physical domains to create a simulation model for the injection system. The components are described using validated analytical models that represent the injection system actual hydraulic, mechanic, and electric behaviour. The 1-st generation Bosch common rail injector model created in the Boost Hydsim environment is shown in Figure 1. Every its internal elements needs to be geometrically and hydraulically characterized to reproduce an accurate behaviour with the injector model. The main injector parameters used in the study are listed in Table 1.

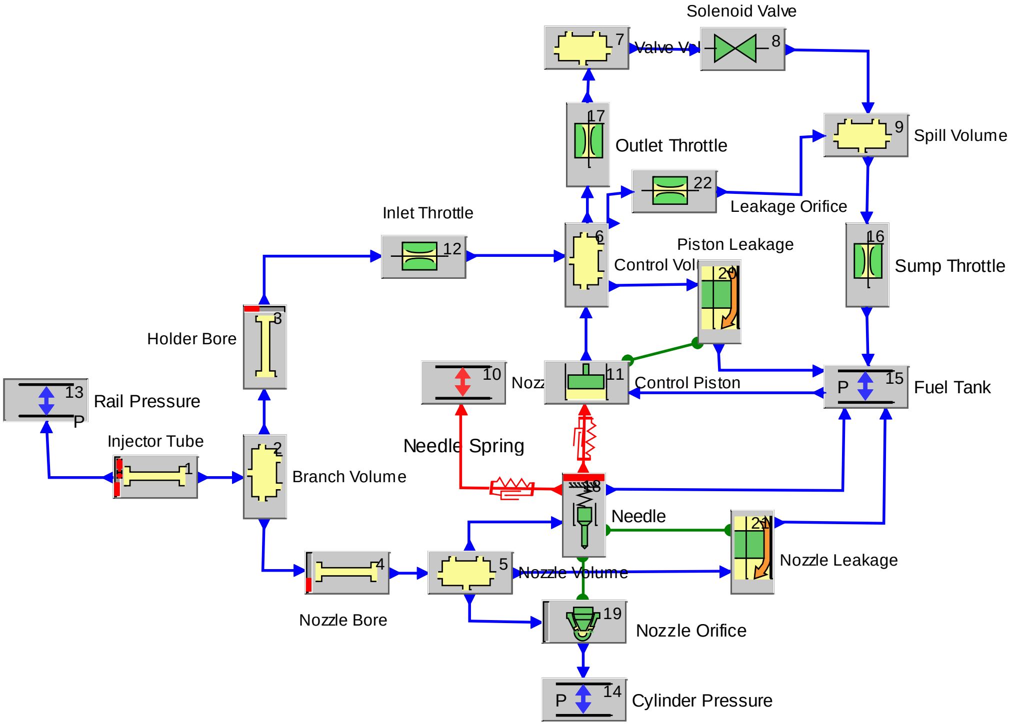

Fig.1. Numerical model of the common rail fuel injector.

Table 1. Injector main parameters

Parameter	Value	Parameter	Value
Nozzle holes	6	Needle seat diameter	1.7 mm
Nozzle hole diameter	0.016 mm	Control chamber initial volume	0.2 mm^3
Needle maximum lift	0.28 mm	Inlet orifice diameter	0.24 mm
Needle mass	2.6 g	Outlet orifice diameter	0.27 mm

The control valve wear was simulated by using an extra orifice 22 between the control chamber 6 and the spill volume 9 (Fig.1.). The simulation was carried out at different cross-section areas of the extra leakage orifice of 0.02, 0.04 and 0.06 mm^2.

The manufacturer of the injectors determines conditions for these tests, like fuel pressure and actuation time. The injected fuel quantity and the return quantity are basic quantities measured by the test benches. The most common method of testing the injectors is measuring the injector parameters at the four operating points. The first operating point is a full load mode, which simulates the work of the injector during the engine full-load operation. The second parameter is an emission mode, which corresponds to the medium load of the engine. The third measured point is an idling mode. The fourth measured point is a pre-injection mode. The recommended ranges of correct dosage values of the injected fuel are also provided. This type of tests is relatively fast and allows for the diagnosis of most of the injector malfunctions. The above-mentioned test modes were chosen for modelling in this numerical study (Table 2).

Table 2. Simulated injection modes.

Injection mode	Fuel (rail) pressure, MPa	Energizing time, µs
Full load	130	1000
Part load	50	675
Idle	23	725
Pre-injection	50	250

The validation of the numerical model has been conducted by comparing the injection characteristics and the fuel quantities injected per cycle obtained in the experimental studies and the modelling findings.

RESULTS AND ANALYSIS

The simulation test results show that the wear of the control valve affects the amount of fuel injected and causes back leakages in the system. The amount of the fuel leaking through the valve leaks is decisively influenced by the fuel pressure (Fig. 2). As the injection pressure increases from 50 MPa to 1300 MPa, the fuel flow through the valve leaks increases by 50%, 58%, 61% for the respective values of 0.002, 0.004, and 0.006 mm^2 accepted in simulation for the control valve leaking cross-sections. An increase in pressure within the lower range of 23 to 50 MPa causes an increase in the fuel leakage of 51%, 45%, and 47%, respectively, for the tested cross-section areas.

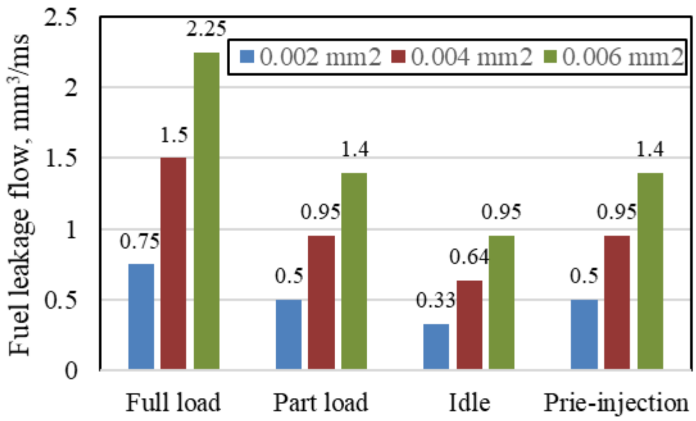

Fig.2. Effect of common rail pressure on the fuel leakage at various simulation modes.

Fig. 3 demonstrates the effect of the fuel leakage on the amount of fuel injected caused by a leakage in the control valve of the CR fuel system. The leaking cross-section of control valve preset at a minimum value of 0.002 mm^2 increased the amount of fuel injected by 5.25% for maximum load mode. While with the double bigger cross-section area of the leaks, the amount of fuel injected increases by 10.5% compared to that volume of the fuel-injected with a proper injector. At the biggest cross-section leakage area, the content of the fuel-injected per cycle (ms) increased by 16.4% against its initial value obtained with a proper injector.

The effect of control valve leakage is even greater when simulating the operation at a part-load mode. Even the smallest cross-section leakage area analyzed in the study the fuel portion injected increases by 25.4% against its initial value. While at higher leakages simulated, the volume of the fuel portion injected increases by as much as 54.8% and 87.4%, respectively. Of course, the electronic control system of the engine manages to compensate for the increased fuel portion by reducing the duration of the injector control

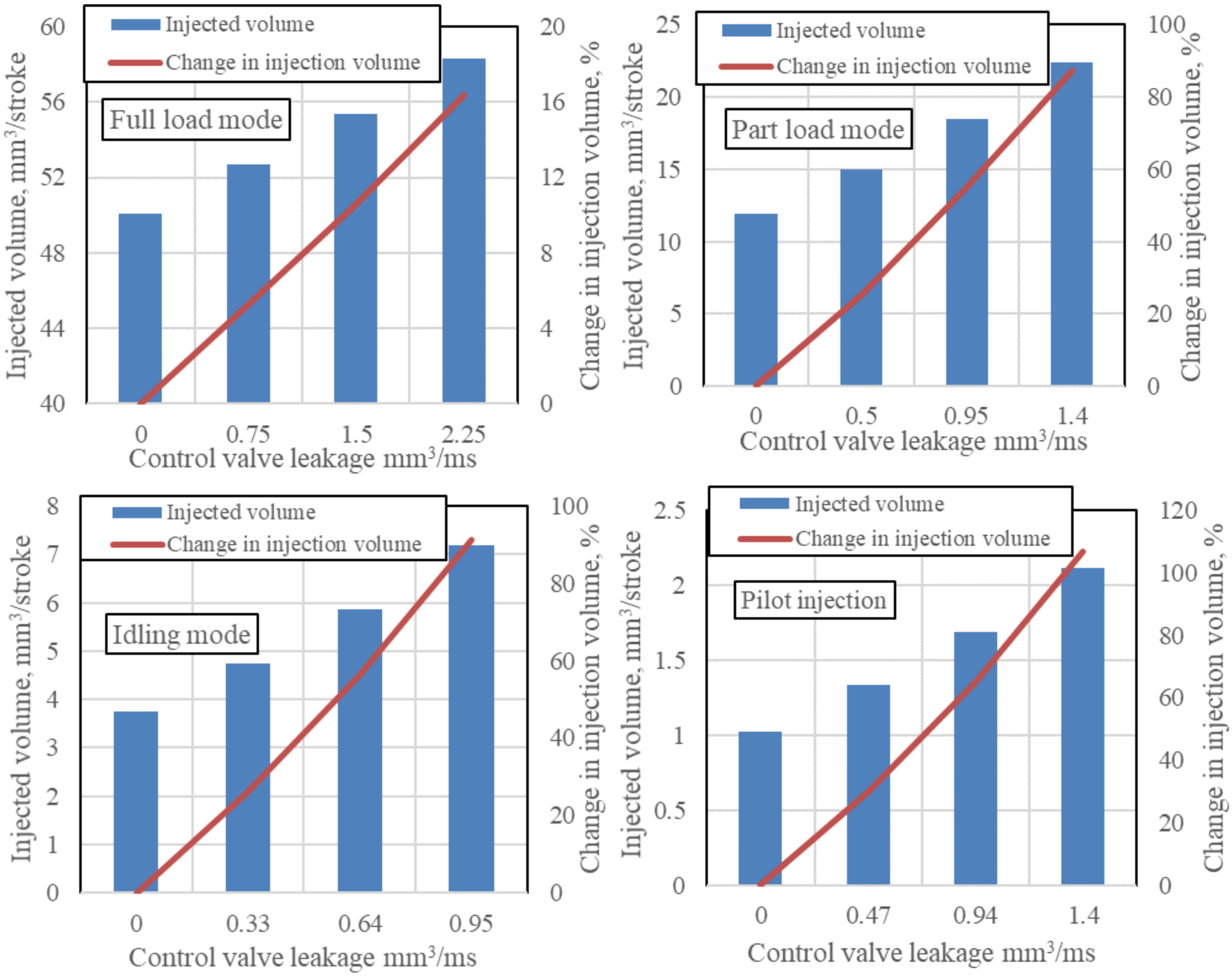

Fig.3. Influence of back leakage on the amount of the fuel injected per cycle.

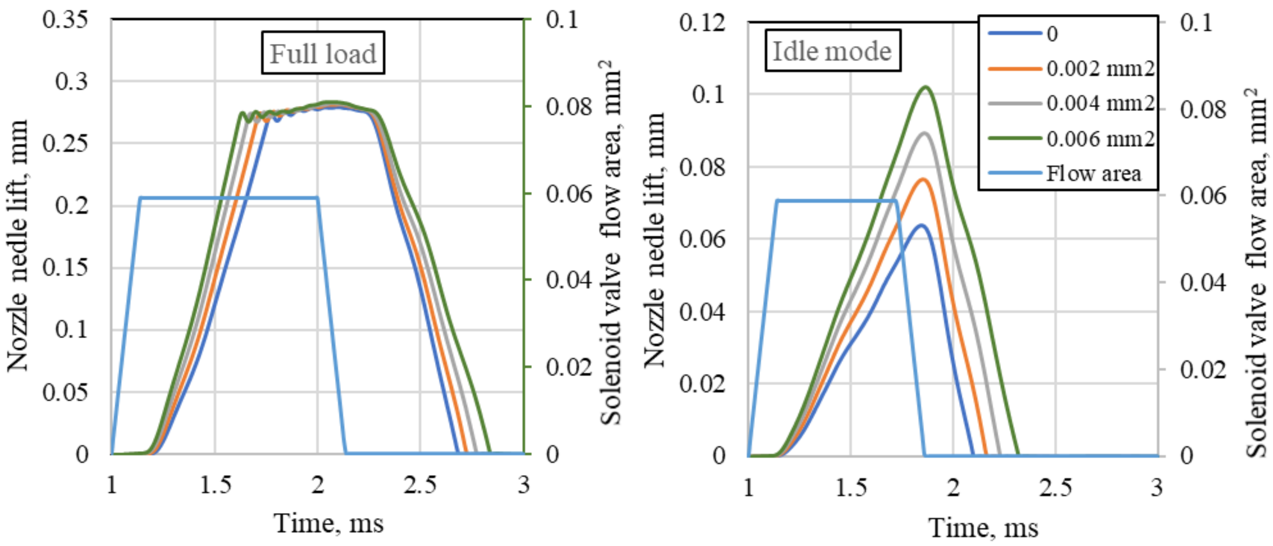

Fig.4. Influence of back leakage on the nozzle needle lift.

pulse. However, in the transient modes, especially during engine acceleration, the portion of the fuel-injected will significantly exceed the required amount to correspond to the actual air-mass flow rate. This fact will increase the number of harmful substances emitted into the atmosphere, especially particulate matters (PM).

A similar effect of control valve leakage was also obtained in the idling mode (Fig. 3). In this case, the fuel portion injected increases by 26.2%, 56.2% and 91.3%, respectively. This, in turn, can affect the stability of the engine operation at idling mode.

However, a leak in the control valve has a relatively the greatest effect on the pilot injection fuel portion. This mode of operation characterizes by a sufficiently high pressure of 50 MPa and a short injection time of 250 μs. In such a case, the fuel portion during pilot injection increases by 30.2%, 65.1%, and 106.8%, respectively. The revealed increase in the amount of pilot fuel injected can negatively affect the combustion of the main-fuel portion. The effect of the control valve leakage is higher the higher rail pressure and the shorter the duration of fuel injection.

Fuel injection begins when the injector needle rises from the seat and ends when it returns to the seat and closes the injection holes. As can be seen in Fig. 4, as the control valve leakage increases, the nozzle needle rises earlier in the cycle to the support and descends back later at the maximum load mode. This means that the injection time gets longer (extends) and, as a result, a higher volume of the fuel is injected. While the nozzle needle does not complete the full stroke when running at lower load modes (partial load, idling mode, or pilot injection). It should be noted that as the leakage increases, the nozzle needle not only rises faster (earlier), but its total stroke (lift) also increases. This change results in a significantly higher increase in the amount of fuel injected.

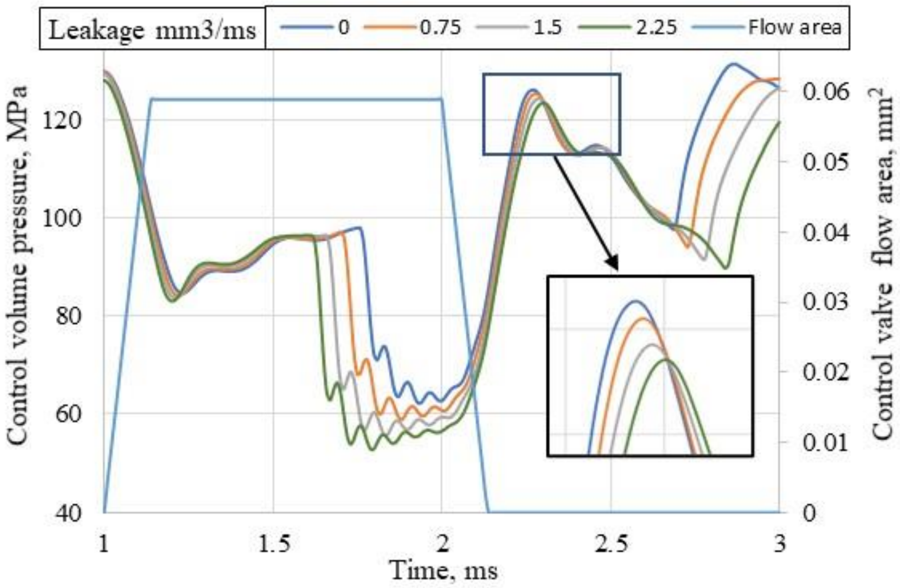

Fig.5. Influence of back leakage on pressure alternation in the control chamber.

The nozzle needle pressed against the seat keeps the fuel pressure in the control chamber. The opening and closing of the injector largely depend on the fuel pressure changing traces in the control chamber. As it follows from the analyses of pressure variation curves shown in Fig. 5, the pressure in the control chamber drops to the minimum value earlier after the beginning of opening the control valve as the fuel leakage from the control chamber increases. On the contrary, the pressure in the control chamber rises to the maximum value later in the cycle when the control valve closes the outlet orifice. In addition, the maximum pressure in the control chamber establishes at a slightly lower level than the common rail pressure due to the continuous leakage of the fuel from the control chamber. Namely, the noted fuel pressure changes in the control chamber determine the changing trends in the amount of fuel injected.

CONCLUSIONS

A numerical model of a common rail injector 1-st generation was developed in AVL BOOST Hydsim environment to perform simulation of the effects caused by the control valve wear. It is revealed that the control valve leakage has the biggest effect on the behaviour of pressure changes in the control chamber and therefore on the amount of fuel injected.

1.The amount of fuel injected increases with the increase in the control valve leakage. The effect of the control valve leakage is higher the higher rail pressure and the shorter the duration of fuel injection.

2.Pressure in the control chamber drops dawn to the minimum value earlier after the start of opening the control valve and rises to the maximum value later in the cycle when the control valve closes the outlet orifice as the fuel leakage from the control chamber increases.

3.When the control valve leakage increases, the nozzle needle-valve rises earlier and descends back to the seat later in the cycle.

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Лабецкас Г., Славинскас С., Мицкявичюс Т. Численное исследование влияния утечки управляющего клапана на работу CR форсунки.

В статье представлены результаты численного исследования влияния протечек управляющего клапана на работу Common Rail (CR) форсунки. Для решения исследовательских задач в среде AVL BOOST Hydsim разработана численная модель форсунки CR 1-го поколения. Выявлено, что утечка управляющего клапана оказывает наибольшее влияние на характер изменения давления в камере управления и, в свою очередь, на величину цикловой подачи топлива. Количество впрыскиваемого топлива увеличивается с увеличением утечек через неплотности управляющего клапана. Влияние утечек топлива через неплотности изношенного клапана тем выше, чем выше давление в топливном аккумуляторе и меньше продолжительность впрыскивания топлива. При увеличении утечек топлива из камеры управления, давление в камере падает до минимального значения ранее после начала открытия управляющего клапана и повышается до максимального значения позже после закрытия выпускного отверстия управляющим клапаном. Вследствие упомянутых изменений в управляющей камере игла распылителя форсунки поднимается раньше и опускается в седло обратно позже в цикле.

Ключевые слова: common rail, топливная форсунка, численное моделирование, шариковый клапан, негерметичность, дизельный двигатель.

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