Thermal shock testing for Engines in Dymola

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Abstract

In this work, we use an acausal multi-domain physical system model to study the interaction between an internal combustion engine operation and a range of cooling scenarios. Although the model can be used for modelling a wide range of scenarios, in this paper we concentrate on the application of “thermal shock”. An internal combustion engine is load-controlled on a dynamometer and coolant temperature transients are imposed on the engine system. Using freely available and commercial Modelica Libraries within the Dymola environment, the whole system integration of the coolant rig and engine dynamometer is achieved. This allows the user to develop and define control strategies for the tests from desktop, prior to engaging in the real tests.

Keywords: Engine testing, thermal-shock, control system development

1 Introduction

Engines need to work under a variety of temperature conditions. Some engine failure modes are caused by temperature cycling which in turn causes thermal expansion and contraction. This phenomenon can induce mechanical stresses which in extreme cases can lead to component failure.

When an engine starts working it generates heat. This waste heat causes the engine components as well as the oil and coolant temperatures to rise. A thermostatic valve is used to ensure the engine and its fluids reach and maintain the optimum operating temperature for the duration of its use.

The thermostatic valve [1] remains closed during initial engine operation until the coolant temperature exceeds a set point. The thermostat then opens completely and a certain amount of cold coolant flows into the engine. Repeated hot/cold thermal cycles are the cause of the head gaskets failure.
If the cylinder head is kept cooler than the cylinder block, the block and the head will expand at different rates. These non-homogeneous head contractions and block expansions produce strain stresses on the head gasket. Even if the cooling system works well, repeated power on/off cycles will produce cracks on the head gasket surface. The head gasket is the most vulnerable part of any engine and a head gasket failure may result in catastrophic damage to the engine.

The non-homogeneous expansions and contractions of the engine block and head are especially significant with aluminium cylinder heads because aluminium expands approximately two times as much as cast iron when heated. The difference in thermal expansion rates between aluminium head and cast iron block combined with the stress caused by thermal cycles can cause the cylinder head gasket failure.

2 Thermal Shock Testing

Many manufacturers carry out thermal shock tests to understand and prevent component failure, as well as to accelerate durability testing of engines and engine components, including cylinder-head gaskets.

Thermo-mechanical fatigue is the term used to describe the type of fatigue in which temperature is varied through a cycle. The maximum tensile strain occurs at the same time as the maximum temperature. Maximum compressive strain occurs at the minimum temperature. The main factor causing thermo mechanical failure is a large number of temperature cycles.

As in fatigue testing, it is possible to accelerate thermal cycling failure modes by increasing the frequency or amplitude of the thermal cycles. These thermal tests are used to simulate critical conditions inside the engine circulating a coolant flow with very large temperature gradients in short periods of time (e.g. 30ºC to 120 ºC). This is repeated cyclically.

The main task to be performed is to simulate repeated hot/cold thermal cycles. The engine is cycled between rated power and low idle. The coolant is also cycled between hot and cold respectively by means of an external conditioning unit.

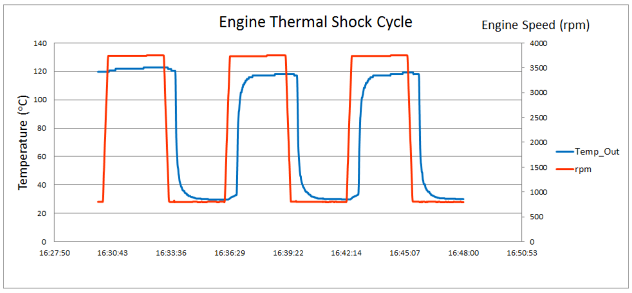

Figure 1: Example of an engine thermal shock cycle. Engine speed shown in red and coolant outlet temperature from engine shown in blue (ºC).

The temperature gradient in the warm up and cooling down cycles is critical to the mechanical stresses applied to the engine due to the thermal shock.

These kinds of tests allow manufacturers to reproduce the whole life of an engine in about 500 hours for a light duty passenger car and 2000 hours for a heavy duty vehicle.

Manufactures expend great efforts in obtaining a good correlation between specific tests and the actual life time of an engine. Once the correlation is completed, the test must be performed as accurately as possible to preserve this correlation.

3 Necessity of a Simulation Model

The interaction of an engine cooling system and coolant over time leads to complex equations which need to be integrated versus time in order to predict the cooling and heating ramps the engine will experience.
Adding the thermal shock equipment responsible for the temperature cycle control increases the complexity of the problem.

The requirement to design a system capable of following a specific temperature profile over time with high accuracy, guaranteeing fast temperature gradients, implies the need to develop simulation models capable of dealing with this problem.
Existing simulation tools available within AVL (e.g. AVL boost) do not cater for multi-domain systems engineering where various systems performing different functions are integrated with one another. They are more specialised tools used for simulation particular types of system. When there is the need to simulate such diverse types of systems integration, Dymola through the Modelica language serves its purpose.

4 Case Study

A thermal shock unit is designed to test different Diesel engines with powers rating from 8kW to 150 kW and weights rating from 125kg to 556 kg.

Thermal shock must be performed measuring engine coolant outlet temperature and cycling from 30ºC to 120ºC.

4.1 Thermal Shock Equipment Concept

The equipment consists of two coolant tanks each with a capacity of 1500 litres. One tank is are held at a high temperature (120ºC) and one at low temperature (30ºC). Two additional tanks installed in proximity of the engine and serve as an engine outlet pressure control. Pumps and valves control flow which is circulated and bypassed in the engine creating the thermal shocking of the engine.

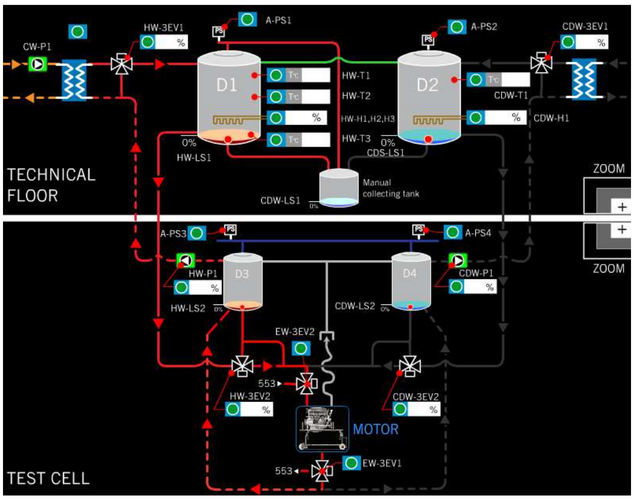

Figure 2: Example of an engine thermal shock rig showing the main components and routing, including the equipment split between the technical floor and the test cell.

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4.2 Thermal Shock Testing Equipment

The unit is divided in two main modules, one installed in the technical floor containing the main tanks.

Figure 3: Thermal shock rig (technical floor side) with hot (left) and cold (right) tanks.

A second one installed in the test cell with the switching valves and the pumps.

Figure 4: Thermal shock rig (test cell side) with test bed (blue), routing valves and pipes on the left.

5 Model Development

5.1 Engine Model

The engine model is based on the Claytex Engines library which offers a wide range of engine configurations and component detail scenarios [2], [3], [4], [5].

The engine model used in this example is a 2.2l common rail turbo-diesel inline 4 cylinder engine. It is a Mean Value engine model where the intake and exhaust air paths are modelled [6] as well as the emissions, pressure charging, torque generation and fuelling. The engine mechanics is multi-body in type utilising the efficient rotational 3d components from the Claytex library. The Claytex rotational 3d library components allow multi-body modelling with comparable computational efforts to a 1d mechanical system, and have been used throughout our projects.

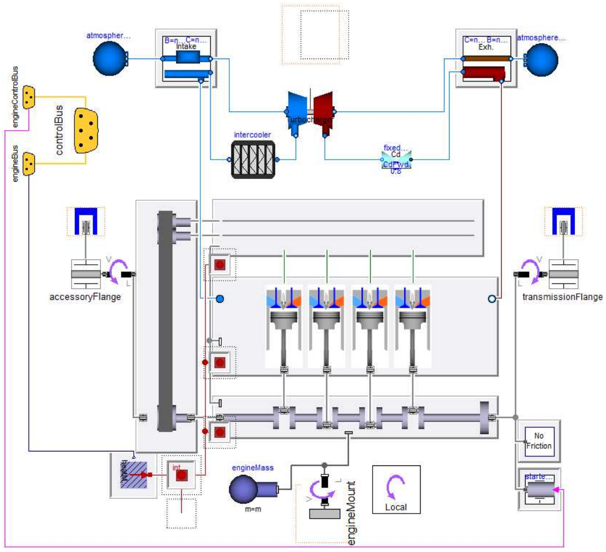

Figure 5: Mean Value engine model with replaceable mechanical and fluidic subsystems.

The engine is coupled to a torque based Engine Control Unit which specifies the fuelling and torque required but also controls ancillaries such as the turbocharger wastegate.

The engine heat release to coolant has been defined as a fraction of the crank power and varies depending on engine speed and load. The fraction value is determined from steady state tests by calculating the power to coolant required for the coolant temperature change between the coolant inlet and outlet of the engine. The coolant path within the engine is represented by a single pipe having average diameter of the passageways and the measured total engine coolant pathway volume and surface area. The pipe diameter is adjusted to achieve the required coolant flow speed through the engine.

The engine thermal mass in this case is a lumped thermal mass and is not split by component. More detailed models are available within the Claytex Engines library for studies which require higher level of engine thermal mass discretisation.

The engine dynamometer is controlled via a rig controller which can load or motor the engine according to the experiment requirements.

The turbocharger system is Stodola/Ellipse [7] based and yields a dynamic response. The heat release from the combustion is channelled through 1d thermal ports to the engine coolant system and rig.
The coolant pump of the engine is replaced by electric coolant pumps within the rig which can be controlled to deliver specific flows or flow profiles.

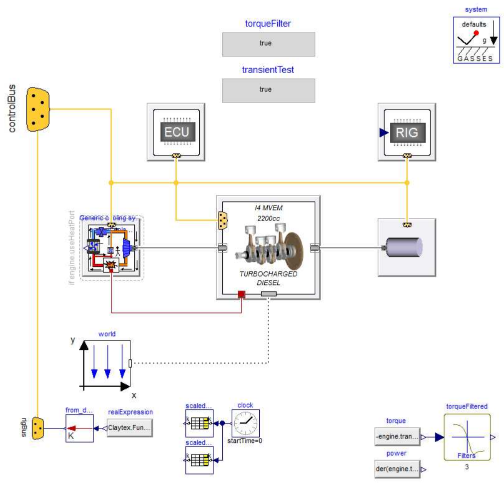

Figure 6: Mean Value engine model mounted on test bench with coolant system based on thermal shock test rig.

The heat transfer from the engine to the coolant is calculated by means of a Nusselt Number correlation, calculated specifically for this engine. The Nusselt Number correlation is then used within the pipe model which represents the coolant path within the engine. Due to the fact that the thermal mass of the engine is of lumped type, the volume model used to represent the mass of coolant within the engine has one thermal node. The same Nu correlation can be implemented with multiple node fluid pipes derived from the Modelica.Fluid library should a more detailed thermal discretisation be required. The exact same Nusselt Number heat transfer approach is used for the heat exchangers in the rig model described in section 5.2.

5.2 Rig Model

The coolant rig must be able to supply preconditioned engine coolant to the engine at two or more different temperatures. The rig described in this paper uses two 1500 litre tanks kept at temperatures with fixed set-points. One tank is kept at a high temperature and the other at a lower temperature. Typically these temperatures are ambient and fully warmed up engine coolant temperatures. The tanks are required to also smooth out and absorb any temperature fluctuations in the rig coolant.

At particular points in the cycle two 3-way valves are controlled to channel either hot or cold coolant through the engine. This change in coolant temperature yields the required thermal shock for the engine to experience and operate through. The tanks should be sized big enough to be able to absorb any fluctuations in coolant temperature even after switch over of the 3 way valves.

Figure 7 Example of 3-way valves used in the rig to route the coolant from each of the tanks through the engine.

The hot and cold tanks are controlled to their set-points by the use of a water to water heat exchanger (for cooling the fluid down) and a heating element mounted in the tanks for increasing the tank coolant temperature. It is required that the tank temperatures are returned to their desired set-point prior to each tank circuit being re-routed through the engine water jacket.

The rigs are modelled using the Modelica.Fluids and Modelica.Media libraries [7] with some customized components from the Claytex library which incorporates some advanced functionality within the components both for visualization and enhanced model efficiency. The fluid used matches that of the rig in terms of properties and is a mixture of 50% Ethylene Glycol and water with linear compressibility.

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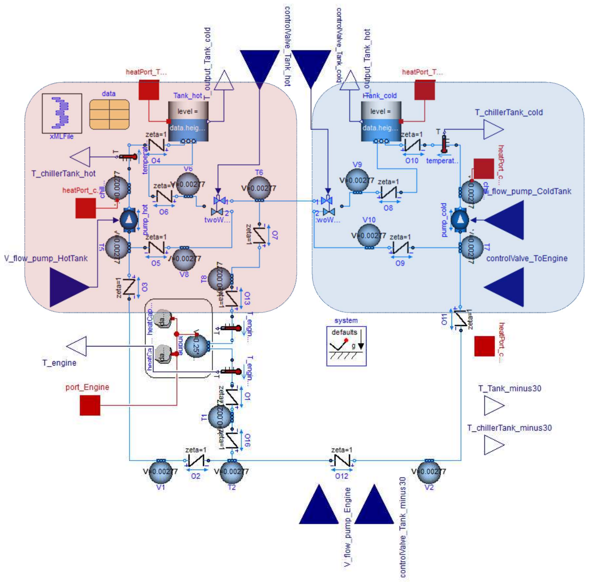

Figure 8: Thermal shock rig with hot (left) and cold (right) circuits.

The controllers for the tank heaters and coolers are of PID type and tuned to account for the power of these components and the response required of the system.

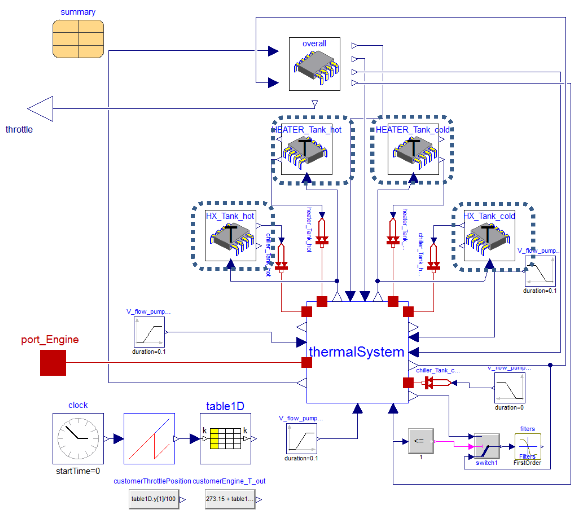

Figure 9: PID controllers for controlling the heat exchangers and heaters to maintain tank fluid temperatures close to the set-point.

If the tank fluid temperature has strayed from the set point, the heater and cooler and associated controller need to be sized and parameterised appropriately so that the set-point temperature can be restored prior to the next hot or cold cycle.

To control the 3-way valves a Modelica.StateGraph model was created (Figure 10). At particular points in the cycle the valves are operated to route the hot or cold coolant through the engine. The same State-Graph model controls the throttle pedal position which is cycled from 0-100% in a similar phase to the engine speed (Figure 10).

The PIDs for the tank heaters and cooler control were optimised to achieve minimal deviations (1-3 ^{o}C) during the cycles.

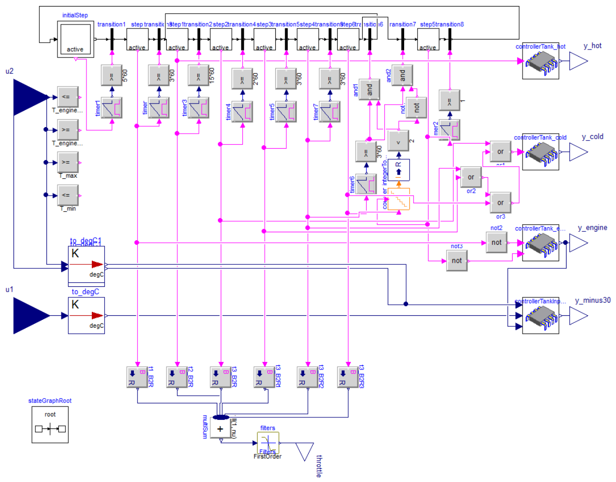

Figure 10: StateGraph controllers for the 3-way valves.

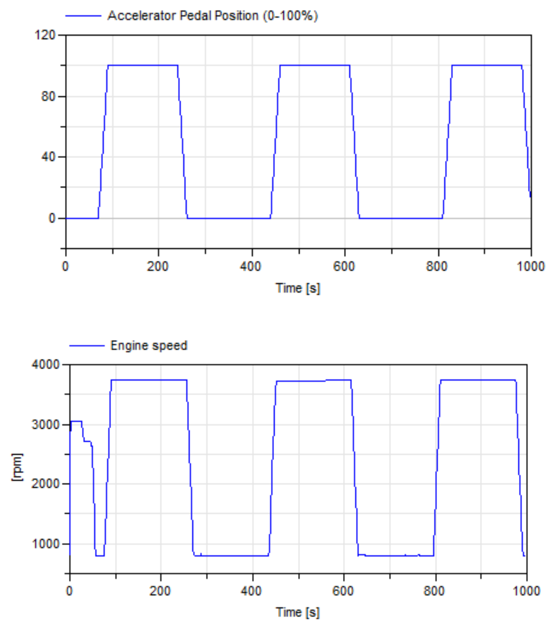

Figure 11: Resulting accelerator pedal position (top) and engine speed (bottom) for the thermal shock test.

6 Results

The integrated engine and coolant rig, as shown in Figure 5, yielded close results to those measured on the test bed with some minor discrepancies on the hot part of the cycle when the engine is operating at full power. We analyse the engine coolant in and engine coolant out temperatures as shown in Figure 12. Firstly we consider the accuracy of the inlet coolant temperature to the engine. If the temperature of the coolant at the engine inlet is not accurate then this will influence the exit temperature and potentially reduce the accuracy of the model. Discrepancy in the coolant inlet temperature after ramp up and ramp down ranges from 0.4-0.85°C. This type of error is deemed acceptable and demonstrates that the conditioning system is sized and modelled correctly.

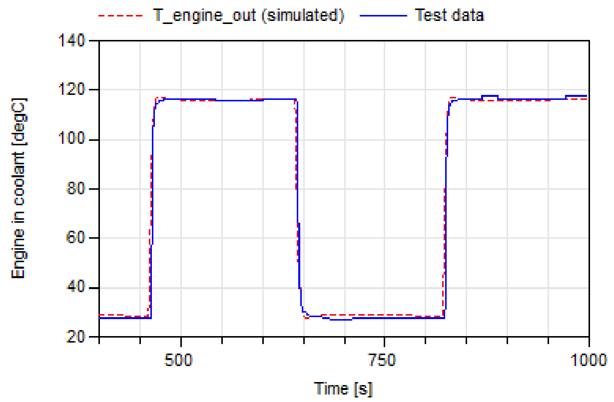

Figure 12: Engine coolant inlet temperatures for test data (blue) and simulated data (red dashed).

Being satisfied with the coolant inlet results we now concentrate on the engine coolant outlet results. This is the coolant temperature exiting the engine. We notice the ramp downs (shown in Figure 13) at t~ 250s and t ~650s are offset in time. Initially we get a faster cooling of the modelled engine but as the coolant temperature approaches the cold circuit temperature (27 °C) the modelled coolant temperature transient slows down. Nevertheless we note that the lower temperature is achieved prior to the coolant temperature increase ramps at t~470s and t~830s. On the temperature increase ramps the engine coolant heats up marginally quicker than the test shows and overshoots the test data at the higher coolant temperatures t~600s, t~950s by approximately 0.3-1°C.

The high temperature sections correspond with the engine being at full load and speed. The overshoot tells us that there is excess heat being put into the coolant by the engine at maximum power in the model.

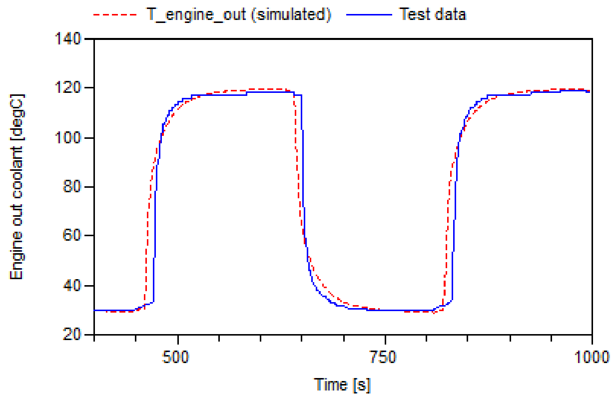

Figure 13: Engine coolant outlet temperatures for test data (blue) and simulated data (red dashed).

The minor discrepancy in the transients is believed to be linked to the correction required for heat rejection of the engine to the coolant and potentially the thermal mass of the engine itself.

The whole system model on average is shown to run faster than real-time with both variable (Figure 14) and fixed step (Figure 15) solvers, the latter making it suitable for hardware-in-the-loop simulation. For fixed step solver the target turnaround time is 1ms. There are occasional spikes denoting overruns (Figure 15) which can be accommodated for. Further improvements in event checking suppression should allow the reduction if not removal of these spikes.

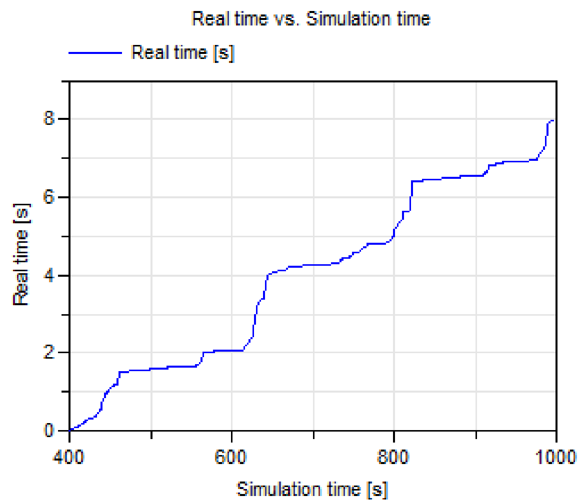

Figure 14: Model performance using Radau IIa variable stiff solver for stiff systems showing Real time (vertical axis) vs. simulation time (horizontal axis).

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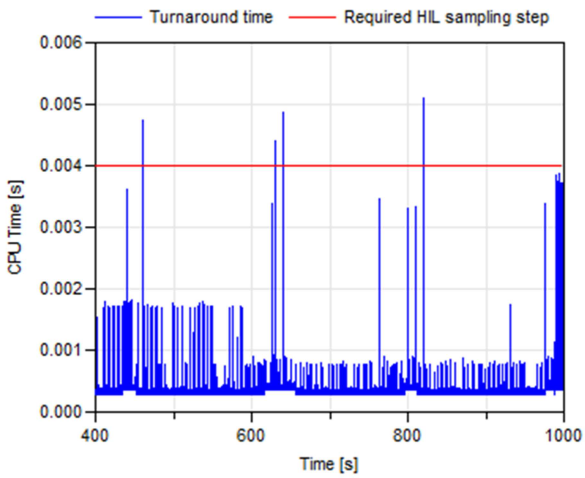

Figure 15: Model performance using Euler fixed step solver and implicit inline integration showing CPU time per calculation step (vertical axis) vs. simulation time (horizontal axis)

7 Conclusions

This paper shows how a highly complex multi-domain system to reproduce engine thermal cycling scenarios such as "Thermal shock" can be created within Dymola. Detailed physical representation of the internal combustion engine as well as the coolant rig, valves and controllers has been achieved. The acausal and multi-domain properties of the Modelica language make it possible to simulate all these integrated systems within one larger system model without the need to interface with third-party tools.

Despite the model complexity it will run faster than real-time. Symbolic manipulation plays a large factor in this reducing the number of equations to be solved from in excess of 27000 to just over 3700.

The model will allow the user to specify and define appropriate components and control strategies used to test engines without actually having to use a real engine. This in turn reduces costs, pollutant emissions and the time involved in calibrating a rig and controller with the internal combustion engine fitted and run.

Lastly, the model has been shown to achieve real-time simulation with Euler fixed step solver and implicit inline integration making it suitable for HIL applications.

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