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IMPACT OF THE HEAT TRANSFER COEFFICIENT OF THE EXTERNAL MEDIUM, CORRECTIONS OF THE VISCOSITY AND PRESSURE ON A SIMULATION OF A RESTART USING OPENFOAM

Vítor Figueirôa Ventura
Roney Leon Thompson
Universidade Federal do Rio de Janeiro, Avenida Athos da Silveira Ramos, 149 - Ilha do Fundão, Rio de Janeiro
vitor.ventura@mecanica.coppe.ufrj.br
rthompson@mecanica.coppe.ufrj.br
João Felipe Mitre
Universidade Federal Fluminense, R. Miguel de Frias, 9 - Icaraí, Niterói
jf_mitre@id.uff.br

Abstract. *This work aims to evaluate the impact of the heat transfer coefficient, number of iterations to correct the viscosity and the pressure drop on a simulation of a restart. A solver that resolves the energy, momentun and continuity equations were implemented in the OpenFOAM platform. This solver can enter in another iteration if the variation of the viscosity is too great. Simulations of restart of a thermo-viscoplastic were made and the impact of the variation of three parameters were evaluated: heat transfer coefficient of the external medium, number of iteration to correct the viscosity and pressure drop in the tube. In the simulations, there was a clear distinction between a high temperature, low viscosity region and a low temperature, high viscosity region. For higher heat transfer coefficients, the region of low viscosity is more concentrated in the center of the tube. For a smaller pressure drop, the frontier of the two regions begins to blur, representing heat exchange between the incoming fluid and the gelled fluid. The effect of the number of iterations to correct the viscosity is negligible*

Keywords: *Restart, OpenFOAM, thermo-viscoplastic, heat transfer coefficient, pressure drop*

1. INTRODUCTION

1.1 Motivation

Stoppages in oil production are common, whether for emergency or routine reasons. In the case of waxy crude oil, stoppages can be problematic due to oil gelation. In particular, Brazil is abundant in waxy crude oil and the development of pre-salt exploration, with exposure to low temperatures for a long time, this problem becomes more pronounced.

This process of gelation hinders the restart process, which is the process of making the stopped fluid flow again. The gelation of waxy crude oil is widely discussed in the academy, for example, paso (2014) work reviews the literature on the topic, addressing issues such as characterization, constitutive models and rheometry. The discussion can be divided into two fronts: studies that aims to characterize the fluid, Dalla *et al.* (2018) as example, and studies related to flow guarantee, Davidson *et al.* (2004) as example.

The gelled oil is difficult to characterize because its properties are pending. several factors. Among them can be highlighted: the cooling rate, the shear rate to which the oil is subjected and the initial temperature of the oil. Because of this, the fluid is difficult to characterize and assess the impact of each factors and the interaction between them is challenging. Other important aspect is that, normally in these tests, oil is subjected to a fixed condition, which is not the case in a pipe. In the case of a pipe, the conditions to which the oil is subjected change according to its location in the pipe.

As for the flow guarantee aspect, it is a common practice to use a viscoplastic fluid, for experiments, or viscoplastic models, for simulations. As examples of works using this approach, Davidson *et al.* (2004) and Mendes *et al.* (2016) can be cited, that uses a Herschel-Bulkley fluid. Considering this aspects, several approaches can be taken.

In a first approach, the propagation of the pressure wave over the gelled fluid length is evaluated and how this impacts the flow of the gelled fluid. Another approach uses a Bingham or Herchel-Bulkley model with some modifications to add thixotropy.

With such difficulty in characterizing and different ways of modeling the fluid, numerical studies on the subject can present great advantages. Numerical experimentation costs much less than practical experiments and can be quickly adapted to better characterize and model the fluid.

In addition, variation of properties according to the position in the tube is possible in numerical studies, but it is not yet present in the literature in the form of experiments. Because of this aspects, simulating a production stop is important, as it portrays the conditions that oil is subjected to during this process and, consequently, one can predict the characteristics of the fluid at each location in the pipe.

1.2 Objectives

The objective of the present work is to develop a solver for the solution of the problem of the restart of gelled oil with a constitutive model for thermo-viscoplastic materials. This solver will be developed on the OpenFOAM free software platform.

In addition to that, this work has the objective of doing simulations of the normal function, stoppage and restart of a pipeflow.

In a complementary way, the work has the objective of evaluate the impact of the following parameters in the process of restart: heat transfer coefficient of the external medium, number of iterations to correct the viscosity and pressure drop.

2. METHODOLOGY

2.1 Third Type Boundary Condition

In this work, the OpenFOAM platform was used to do the simulations. OpenFOAM uses the Finite Volume Method of discretization, very common in fluid studies. Bibliography on the subject is abundant, as is the case of Malalasekera and Versteeg (2007). Regarding the operation of OpenFOAM, every installation of the program is accompanied by a user guide

OpenFOAM does not natively implement the third type boundary condition. However, if the intent is to simulate a submerged pipe, this condition should be used on the pipe wall.

However, there is a native boundary condition called "mixed". Although it is not a third type boundary condition itself, it does have some similarities.

A third type boundary condition for temperature would be characterized by Eq. (1). It imposes a function, represented in the equation by a constant, that the variable and the derivative of the variable added together must match.

$$k\frac{\partial T}{\partial n} + hT = hT_\infty \quad (1)$$

In this case, k represents the thermal conductivity of the fluid, T_∞ is the temperature of the bulk of the medium, h is the heat transfer coefficient and T is the temperature.

The mixed condition, on the other hand, is requested by the user for a gradient, a value and a fraction. These elements will be combined to generate a value that will be used as the boundary condition, as expressed in Eq. (2). Therefore, the value of the variable and the gradient are imposed, as opposed to the condition of the third type, in which they fluctuate.

$$\phi_b = f \cdot fixedValue + (1-f)\cdot(\phi_p + fixedGradient \cdot d) \quad (2)$$

The ϕ_b represents the variable at the boundary, f is the fraction value that the program requires, fixedValue is the value that the program requires, fixedGradient is the gradient that the program requires, ϕ_p is the value of the variable at the center of the control volume and d is the distance between the center of the control volume and the boundary.

However, following the precedence made in Vilums (2011), one can easily use the native mixed condition, to produce a third type condition. For this, it is necessary to linearize the spatial derivative present in the condition of third type. After this procedings, the values that you must enter in the program is listed in the Eq. (3).

$$\begin{aligned} &f = \tfrac{hd}{hd+k} \\ &fixedValue = T_\infty \\ &fixedGradient = 0 \end{aligned} \quad (3)$$

2.2 Solver Development

The first step in the development of the solver was the inclusion of an energy transport equation in addition to the existing equations. For this, we started with the OpenFOAM pimpleFoam.

This solver uses the PIMPLE cycle to solve the momentum and continuity equations. The PIMPLE cycle is a mixture of the SIMPLE and PISO cycles, and it is fairly common in solvers in OpenFOAM.

In a first approximation, only the energy transport equation depends on the result of the linear moment transport equation, with no actual coupling. So, you can first solve the moment equation to solve the energy equation later.

The equation that was inserted in the solver is the Eq. (4). It is a simplified equation of the energy transport equation present on Slattery (1999), only taking into account the convection and temperature diffusion terms.

$$\frac{\partial T}{\partial t} + U \cdot \nabla T = \alpha \nabla^2 T \quad (4)$$

Where t is the time, U is the velocity and α is the thermal diffusivity.

After that, parts of the code that deal with the non-Newtonian behavior were added. There is native non-Newtonian solver in OpemFOAM. The parts of the code referring to non-Newtonian features have been adapted to the new code.

The native non-Newtonian solver was not used because it uses a PISO cycle and, because of that, only calculates the viscosity once per time-step. It was easier to recalculate the viscosity using the PIMPLE cycle.

At this point, the calculation of the viscosity command was placed inside the outer loop of the PIMPLE cycle. In this way, it is possible to define, at the user level only, how many times it is desired to make the external loop, and, in this way, define how many times it is desired to correct the risk.

Although the control made using the PIMPLE loop is often sufficient, it would be better to do a loop exit control using the variation of viscosity.

In this way, the results of the simulation itself are used to evaluate whether to proceed to the next time-step and not always repeat the cycle a fixed number of times.

An external loop was inserted with two exit conditions: if the variation in the viscosity of all cells is less than a certain value or if the number of iterations exceeds a maximum value. These modifications were made in such a way that the maximum number of iterations and the maximum variation in viscosity could be defined by the user.

It was necessary to define a maximum number of iterations, because sometimes the simulation repeated the same time-step an indeterminate number of times, especially in the first steps and when the initial condition provided was not very accurate.

Within this loop, the value of the current viscosity was compared with that obtained in each cell in the last time-step. Therefore it was necessary to make one more loop to pass through all the cells of the domain.

2.3 Viscosity Model

As stated earlier, most studies on restart treat fluid as being viscoplastic, often as Bingham fluid. OpenFOAM already has a modeling for Herschel – Bulkley, so the viscoplastic model present in this work was made from it.

The first change made was the exponential dependence of the parameters on the temperature. A problem for this Herschel-Bulkley model is that, depending on the parameters used, the viscosity tends to zero for very high deformation rates. One of the ways to fix this is with the introduction of a new term.

lastly, it was desired that non-Newtonian characteristics be activated below a certain temperature. This is desired, because for waxy crude oil there is a temperature of crystals appearing and, from this temperature, the fluid would have a non-Newtonian behavior. Therefore, a model was formulated that, from certain temperatures, the terms of the model would enter the equation. the final formula is represented in the Eq.(5). This model is a modification of the model used in Sargentini (2017).

$$\begin{aligned}
&\nu = \frac{\tau + k\cdot\gamma^n + \nu_T\cdot\gamma}{\gamma} \\
&\tau = \tau_{ref}\cdot max((e^{S_\tau\cdot(\frac{1}{T}-\frac{1}{T_{ref}})} - 1), 0) \\
&k = k_{ref}\cdot max((e^{S_k\cdot(\frac{1}{T}-\frac{1}{T_{ref}})} - 1), 0) \\
&\nu_T = \nu_{ref}\cdot e^{S_\nu\cdot(\frac{1}{T}-\frac{1}{T_\nu})}
\end{aligned} \quad (5)$$

Where $\cdot\gamma$ is the shear rate, n is the power-law coefficient, τ_{ref} is the yield stress of reference, k_{ref} is the flow consistency index of reference, ν_{ref} is the reference viscosity, T_{ref} and T_ν are the reference temperatures and the S's are adjustment coefficients for the exponential.

The implementation of the model was not exactly the same as the models presented here for numerical reasons. Sometimes it was decided to establish a maximum or a minimum for the values that the viscosity can assume. Another necessary adaptation is to make sure that terms that depend on the fields calculated in the simulation and that appear dividing in the calculation of the viscosity, as is the case of temperature and shear rate, are not less than determined value, to avoid extrapolating the largest number the computer holds.

With the model, it is possible to plot the stress by the strain rate and by the viscosity by strain rate graphics, as shown in Fig. 1. It can be noted that below a certain temperature, the viscosity is independent of the shear rate and that, after a certain temperature, non-Newtonian effects appear. It is also worth mentioning that there is a maximum viscosity, which was established due to a numerical issues.

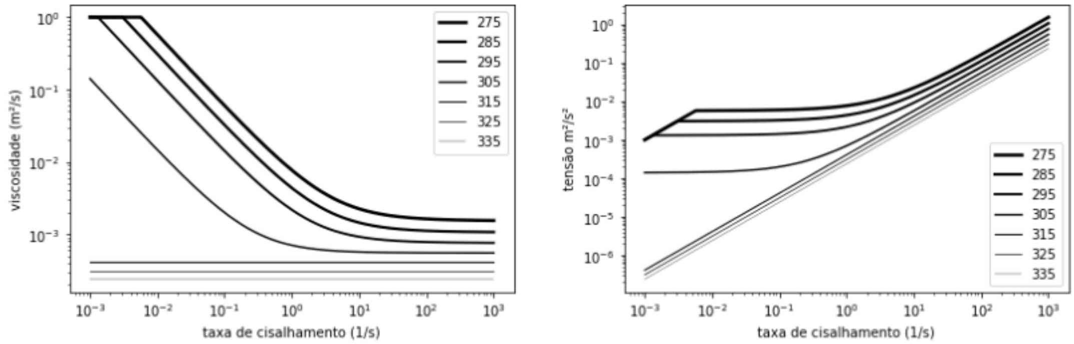


Figure 1. viscosity by strain rate and stress by strain rate graphics of the viscosity model used for various temperatures

3. Case study

The purpose of this work is to simulate the entire process of restart in a pipe. The entire process consists of normal operation, the stop and cool down process and the restart. The numeric scheme used in the advective term was linear for the energy equation and upwind for the momentum equation. As it is a simulation of forced convection, first the momentum equation is solved and then the energy equation is solved. All the equations were solved including the time-dependent terms. The residuals used for convergence was 10^{-7}.

For the simulations, a 5 m long and 10 cm in diameter pipe was used. The simulations were made using wedge geometry that have approximately 5 degrees of opening and it was assumed that the problem was axisymmetric. A grid independence study was made for a similar case but with a shorter tube. It was assumed that the grid using a shorter tube would be enough for this case.

The first step was to simulate normal operation. Normal operation would consist of achieving the permanent regime.

As there was no concern to portray the process until the permanent regime was reached in a reliable manner, it was decided to initially use a coarse mesh and refine until a mesh with the proper refining was reached. The boundary conditions and parameters used are shown in the Tab. 1.

Table 1. Parameters used in the steady-satate simulations

Parameter)	Value
α (m^2/s)	$5 \cdot 10^{-8}$
Δp (m^2/s^2)	10
T_{inlet}(K)	310
k (W/mK)	0.13
T_∞ (K)	277
tau_{ref} (m^2/s^2)	$3 \cdot 3 \cdot 10^{-3}$
$S_\tau = S_k = S_\nu$ (K)	2845
T_{ref}(K)	306.5
k_{ref} (m^2/s)	$25 \cdot 10^{-5}$
n	0.5
ν_{ref} (m^2/s)	$25 \cdot 10^{-5}$
T_ν(K)	333.15

There is a formula widely used in the literature for the pressure required to restart. This formula is show in the Eq.(6). Two simulations were made: one with h = 10 and the other with h = 100 W/m^{2}K

$$\Delta P = \frac{4\tau_y L}{D} \tag{6}$$

Where ΔP is the pressure drop in the pipe, τ_y is the yield stress of the fluid, L is the length of the pipe e D is the diameter of the pipe.

OpenFOAM uses pressure divided by the density, so this will be used in this work. In low temperatures, using the Eq.(6) a pressure of a little above 1 m^2/s^2 is necessary to restart. It was used a pressure of 100 m^2/s^2, so the restart is guaranteed.

Achieving steady state for pressures equal to or less than 1 m^2/s^2 was not always possible. This was only possible for h values less than 1, which according to the work of Zakarian *et al.* (2012), is not very usual for umburried pipelines.

For cooling, an abrupt stop of the fluid was chosen. For a non-compressible fluid, this is a very reasonable approach. Since the fluid is not thixotropic and not dependent on the temperature gradient, for the purpose of restarting, only the temperature at the end of the simulation is relevant.

Because of that, we opted to use the solver laplacianFoam, native to OpenFOAM. This solver just solves the energy equation, making the simulation faster than using the solver described in this work.

The boundary conditions and parameters used are shown in the Tab. 2.

Table 2. Parameters used in the cooling simulations

Parameter	Value
α (m^2/s)	$5 \cdot 10^{-8}$
T_{inlet}(K)	310
k (W/mK)	0.13
T_∞ (K)	277

The simulation of restart is basically using the temperature field obtained in the cooling simulation and applying a pressure gradient. The pressure gradients used were 10 m^2/s^2. Simulations using h=10 W/m^{2}K and h= 100 W/m^{2}K were made. In addition, the number of iterations used to correct the viscosity was 100.

two variations were made from the simulation using h = 10 W/m^{2}K. One using the number of iterations to correct the viscosity equal to 1 and one with a pressure drop of 100 m^2/s^2.

The boundary conditions and parameters used are shown in the Tab. 3.

Table 3. Parameters used in the restart simulations

Parameter)	Value (variation)
α (m^2/s)	$5 \cdot 10^{-8}$
Δp (m^2/s^2)	$100(10)$
T_{inlet} (K)	310
k(W/mK)	0.13
T_∞ (K)	277
tau_{ref} (m^2/s^2)	$3 \cdot 3 \cdot 10^{-3}$
$S_\tau = S_k = S_\nu$ (K)	2845
T_{ref} (K)	306.5
k_{ref} (m^2/s)	$25 \cdot 10^{-5}$
n	0.5
ν_{ref} (m^2/s)	$25 \cdot 10^{-5}$
T_ν(K)	333.15
h(W/m^{2}K)	10 (100)
i	100 (1)

4. RESULTS

It can be noted that the difference in the heat transfer coefficient of the external medium has significant impact on temperature field, as seen in the Fig. 2. All the figures represents only half of the tube and are not in scale. Although in both cases the temperature field has the same pattern, the speed at which cooling occurs is much higher for a greater heat transfer coefficient.

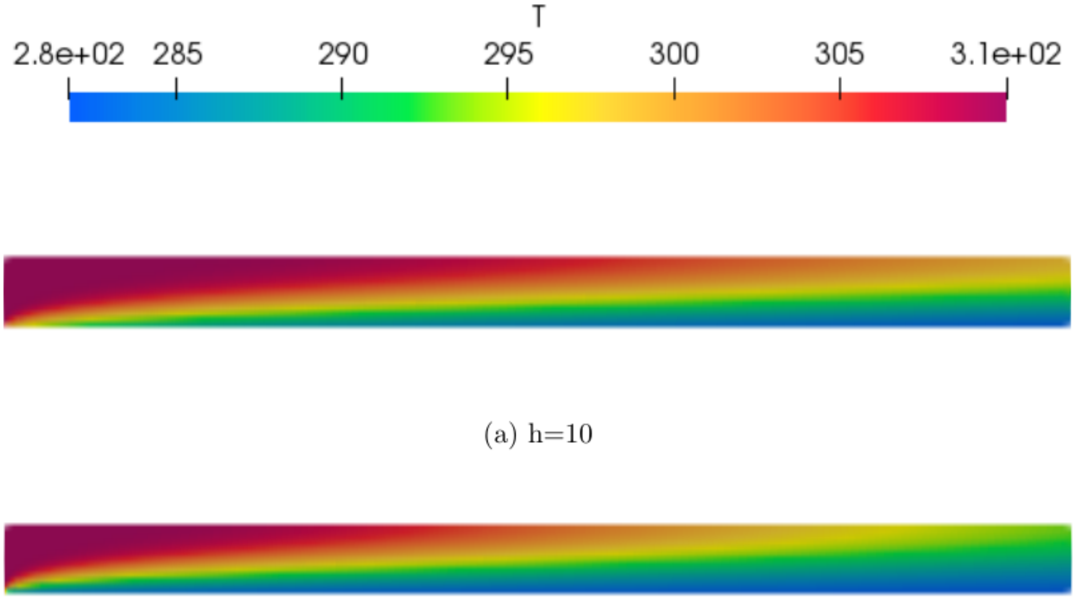
For the velocity field, the difference is not so noticeable. It only possible to note that the maximum speed is greater in the center of the tube for small heat transfer coefficient. It suggests that the velocity profile is flatter for a higher heat transfer coefficient.

There are two competing effects that are relevant to the viscosity field. The closer to the wall of the tube, the lower the temperature tends to be and, therefore, the higher the viscosity. However, the further away from the pipe wall, the lower the shear rate, which also tends to increase viscosity.

In both cases, these concurrent effects result in a V-shaped border separating a region of high viscosity and a region of low viscosity. The difference is just that, for larger heat transfer coefficient, this change occurs closer to the tube entrance.

For the cooling phase, we see in Fig. 5 that, although for a greater heat transfer coefficient the initial temperature in the tube is lower, the temperature field is very similar in both cases after a short period of time.

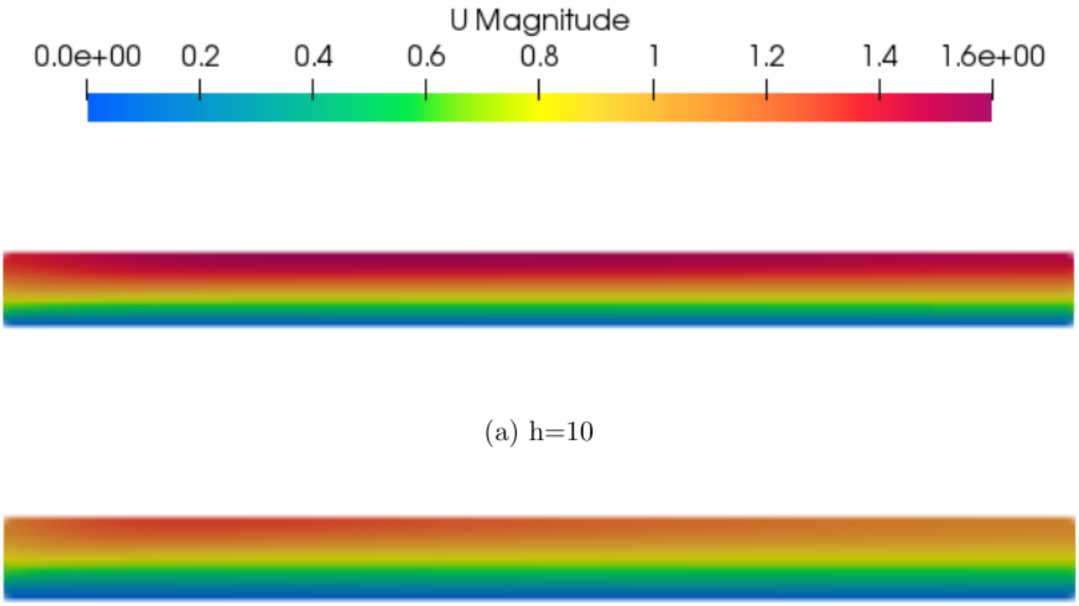
As the pressure drop used was high, the restart process takes place by the hot fluid at the inlet of the tube pushing the cooler fluid. This is very clear when evaluating the speed and viscosity fields. In this work, it was decided to use the



(a) h=10

(b) h=100

Figure 2. Temperature field obtained for the permanent regime using h = 10 W/m^2K and h = 100 W/m^2K



(a) h=10

(b) h=100

Figure 3. Velocity field obtained for the permanent regime using h = 10 W/m^2K and h = 100 W/m^2K

viscosity fields.

There is a clear distinction between this two fluids, separated by a boundary that moves as the flow progress.

Comparing the cases that have a variation of the heat transfer coefficient, we can see little difference. The comparison is made in Fig 6. The biggest difference is that, since there is a greater heat flow through the wall, the low viscosity region is a little more restricted to the center of the tube. There is little difference in the velocity which the boundary between

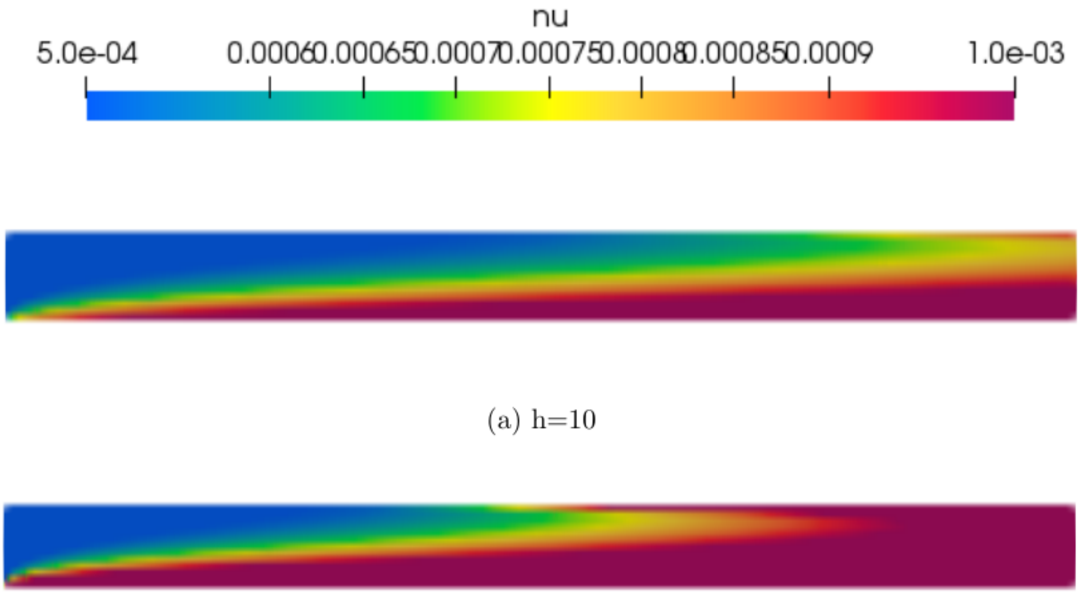


Figure 4. Viscosity field obtained for the permanent regime using h = 10 W/m^{2}K and h = 100 W/m^{2}K

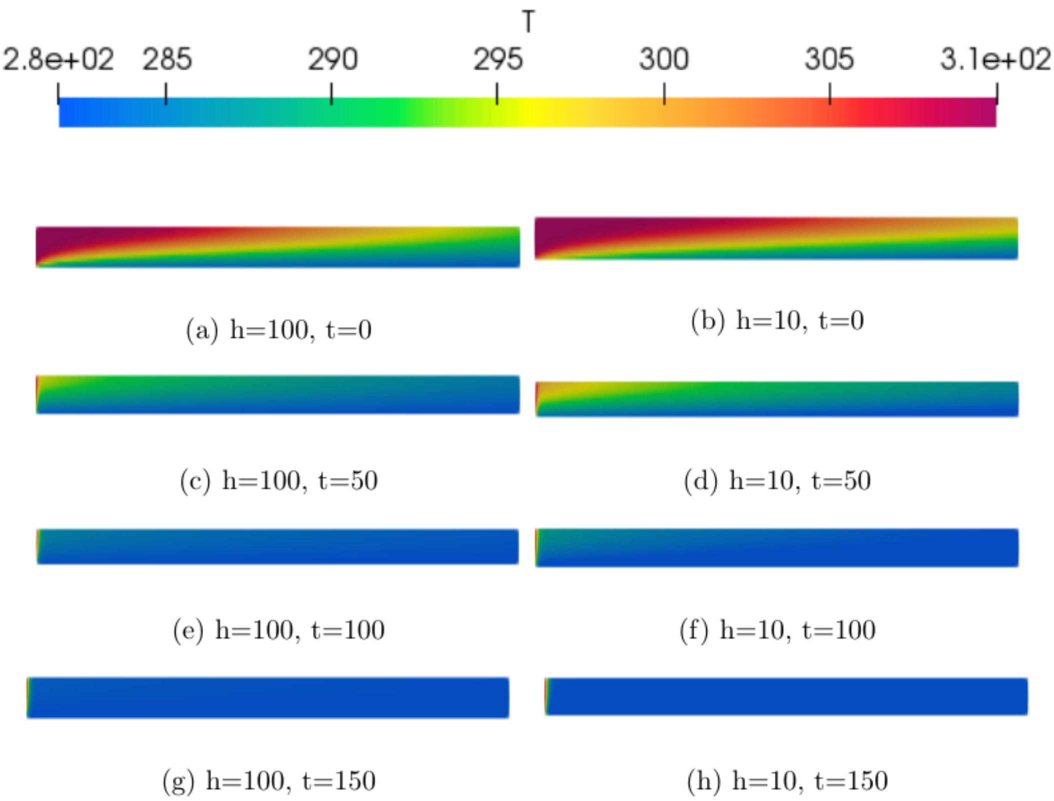


Figure 5. Comparison at different times of the cooling phase between the simulation using h = 10 W/m^{2}K and h = 100 W/m^{2}K

the hot fluid and the cold fluid propagates over the tube.

For the cases where there is a difference in the pressure drop, there is a significant change, as can be seen in Fig. 7. It can be noted that the boundary between the hot fluid and the cold fluid propagates with a much greater speed for a higher pressure drop.

Furthermore, the border between the cold fluid and the hot fluid is much less clear, since there is more time for heat

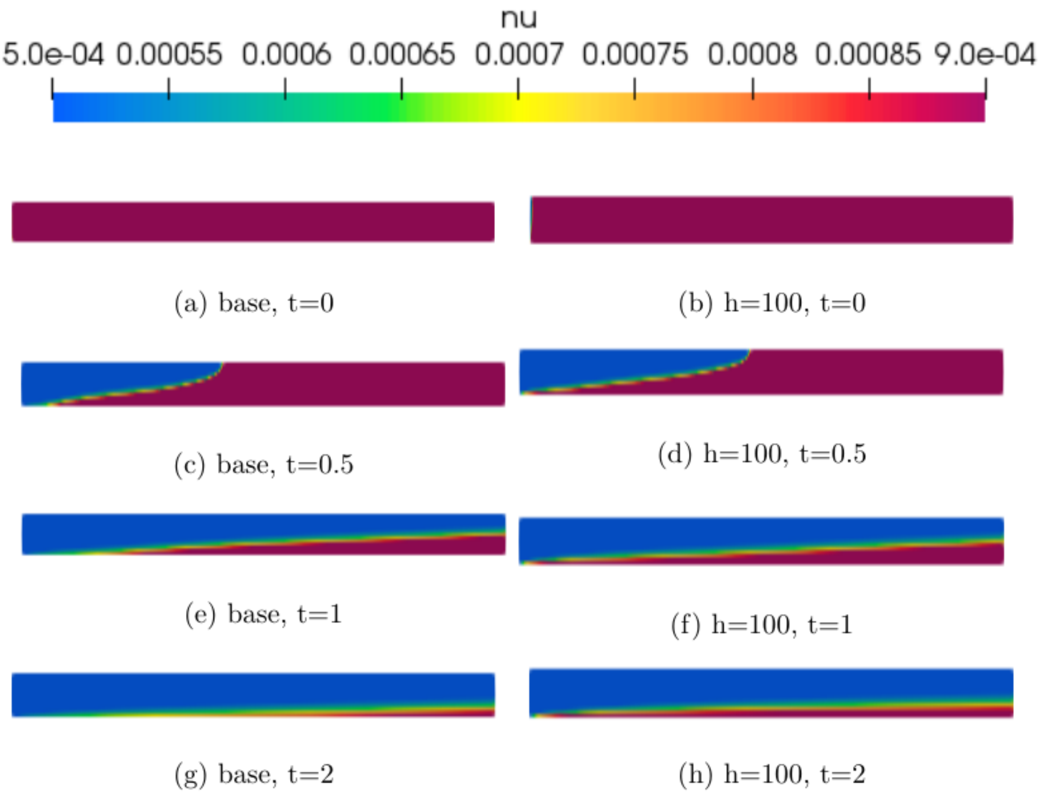


Figure 6. Comparison at different times of the restart phase between the simulation using h = 10 W/m^{2}K and h = 100 W/m^{2}K

exchange between the two regions. Although it is not expressed in the images, for a very long time of simulation using pressure = 10 m^2/s^2 the viscosity field converge to that "V"-shaped boundary that appeared in the permanent regime. This does not occur for p = 100 m^2/s^2.

For the cases where there is a difference in the number of iterations to correct the viscosity, no significant change was noted. This feature is widely used by the solver at the beginning of simulations. During this period, the fluid is cold in practically the entire length of the tube.

If you adjust the scale of the viscosity for this period, you can see that it is not uniform as shown in the first step of time in both simulations, but they do have small variations. However, in assessing the phenomenon globally, these small variations are insignificant close to the variation in viscosity of the hot fluid and the cold fluid as it can be seen in Fig. 8.

5. CONCLUSION

A solver that solves the equations of continuity, momentum and energy has been implemented to the platform OpenFOAM. This solver also has the possibility to reiterate i the same time-step to correct the viscosity. Together, a thermo-viscoplastic viscosity model was implemented.

Using this developed solver and viscosity model, simulations of normal operation, stopping and restarting a flow in a pipe were made. In these simulations, some parameters were varied and their impact was assessed.

Changing the heat transfer coefficient of the external medium is relevant at all stages of the process. Increasing the pressure drop increases the speed at which the restart occurs and also sharpens the boundary between the inlet fluid and the fluid already present in the tube. The number of iterations for viscosity correction has no apparent impact.

6. ACKNOWLEDGEMENTS

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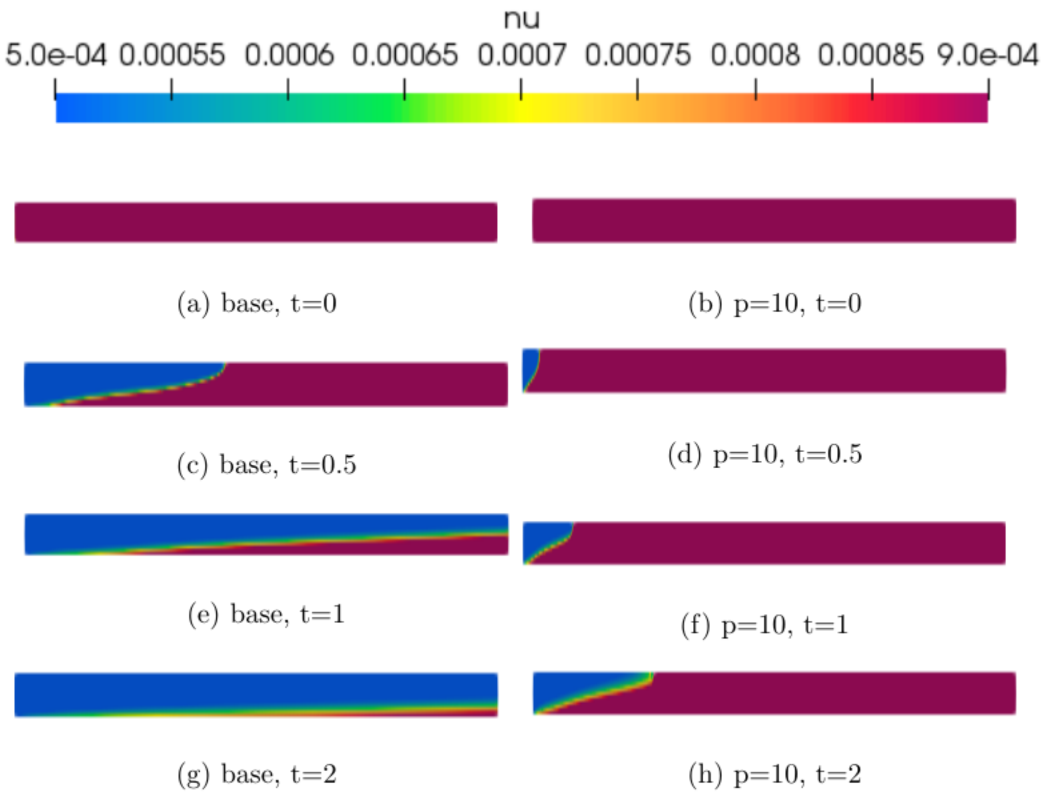

Figure 7. Comparison at different times of the cooling phase between the simulation using p = 100 m^2/s^2 e p = 10 m^2/s^2

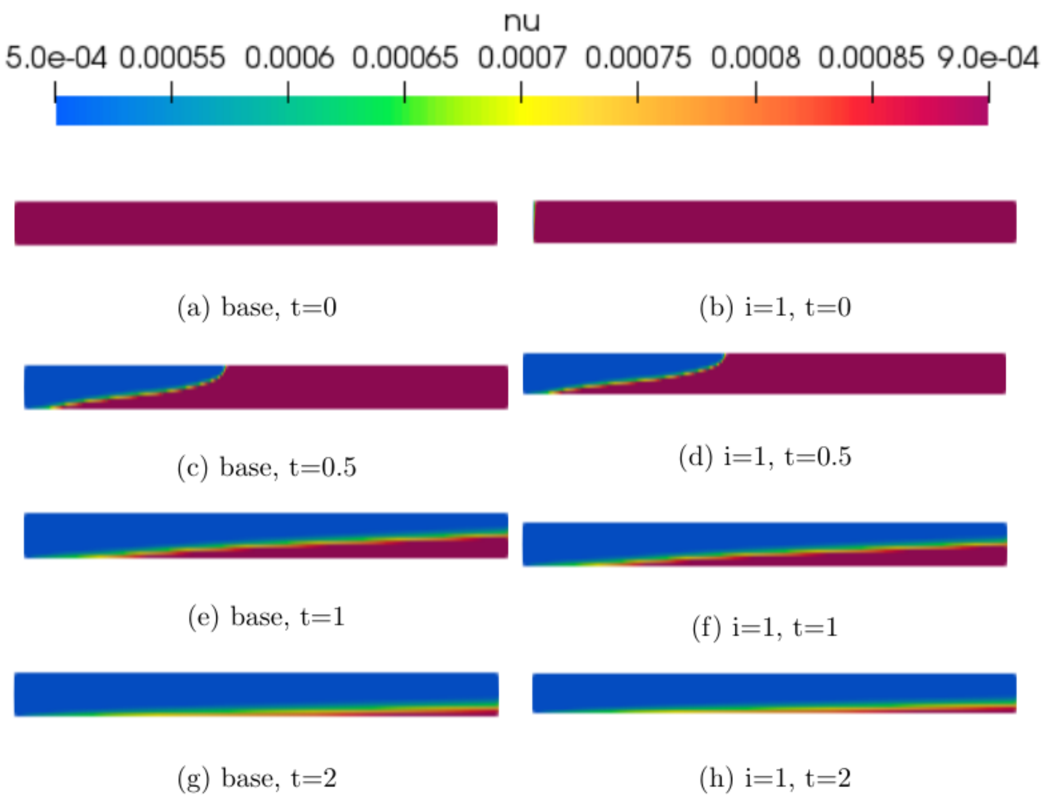

Figure 8. Comparison at different times of the cooling phase between the simulation using i = 100 e i = 1

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