CFD Simulations of a hot gas torch for the thermoplastic tape placement process

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Abstract

Tape Placement with thermoplastic matrix materials is a very promising technology, through its ability to produce extreme lightweight parts without a consecutive process. But it needs a very effective heating system. Among others, the hot gas torch is an appropriate system, but lacks in service durability. The authors intend to improve the service durability of such a system and present here the results of the computational fluid dynamics simulations done in order to design a new type of such a hot gas torch. It shows that through a bad temperature distribution pipe type torches are not appropriate for such a system and a helix type has to be designed.

1 Introduction

As the structure weight is a central concern for the aerospace industry, the amount of fibre reinforced plastics used for structural parts increases rapidly. Therefore the demand for automated manufacturing processes for fibre-reinforced plastic parts also rises. This has strongly driven the development of automated tape laying machines since the 1960’s, because they allow a position and direction dependent placement of unidirectional fibre-reinforced tapes. This is the key to extreme lightweight parts [1].

Beside the tape laying with tapes based on thermosetting matrix materials, which is quite wide spread, it is also possible to used thermoplastic materials as matrix. Thermoplastics generally have some well-known advantages compared to thermosetting resins like the enhanced fracture toughness or the opportunity to thermoform the manufactured part. But the greatest advantage in the context of tape-laying is the ability of an in-situ-consolidation [2]. This means that the bonding of the tapes can be done online and no consecutive process (e.g. autoclave) for full consolidation is needed [3].

The usage of thermoplastics as a matrix material requires that the tape and the substrate is melted before they are bonded together. So the material has to be heated up from room temperature to the melt temperature in a very short time, which is directly related to the processing speed. This means, that a very effective heating system is needed for automated tape laying.

The most common heating solutions to solve this problem are IR-heaters, flame, laser and hot gas torch. IR-heaters are insufficient for high temperature thermoplastics and therefore can only be used for commodity thermoplastic matrixes. Additionally the adsorption of the IRwaves strongly depends on the processed material and they need a huge installation space. The flame is a very effective heating system, but depending on the gaseous fuels the risk of a thermo oxidative degradation of the matrix is quite high [3]. Furthermore, as they use gaseous fuel a lot of safety issues (e. g. ATEX directive [4]) have to be taken into account when using such a flame. Despite the fact that the adsorption also depends on the material, lasers are a very effective heating system. But they need a quite high effort to control the system [5]. Also there are quite huge safety issues to be taken into account (laser class 4 according to DIN EN 60825-1:2008 [6]). The hot gas torch is easy to control and has sufficient power even to heat high temperature polymers. The major advantage of it is that it offers the possibility to us nitrogen as transport gas in order to minimize the thermo oxidative degradation risk. But the in service durability is still quite bad. So the hot gas torch is a very attractive heating system with a lot of research potential in terms of service durability. That's why the authors want to design a totally new type of hot gas torch. The starting point for this research, the computational fluid dynamics (CFD) simulations are presented in this study.

2 Specifications of the hot gas torch

The hot gas torch should be able to heat typical tape dimensions (e.g.: 25,4mm wide and 0,12mm - 0,35mm in thickness) and a PEEK matrix, with a melting temperature around 650K should be possible to process. The maximum processing speed of the tape placement head is defined as 0,33m/s. To ensure a good heating of the whole width, the torch outlet width was defined as 30mm and because of mounting reasons a maximum length of 100mm. As transport gas nitrogen should be used that is preheated from tank temperature to 373K. For fast enough heating the nitrogen flow temperature at the outlet was specified to be at least 1273K and therefore the torch wall will be heated electrically to this temperature. Since the heating of the tape is mostly based on convective heat transport, a high flow velocity at the outlet of the torch compared to the processing speed is desired. In this study it was specified to be at least 10 m/s.

3 Simulation model

All Simulations were performed with OpenFoam 2.1.0™ (OpenFOAM Foundation) using the transient solver rhoPimpleFoam, which is a transient solver for laminar or turbulent compressible flow [7]. The flow was expected to be compressible and turbulent due to the expected density change based on the high temperature gradients. The flow model was the RANS- (Reynolds Averaged Navies Stokes) and the used turbulence model was the k-ω-SST-Model. RANS was chosen because it is the simplest model for compressive, turbulent flows and sufficient enough for the purposes of this study [8]. The k-ω-SST-model has a quite good accuracy inside and outside the boundary layer of the wall [9], and therefore seemed to be the appropriate for this study. For lack of material data for pure Nitrogen the simulations were performed with air as transport gas, but as air consists mostly of nitrogen, and the other components are quite similar to nitrogen, the results should be comparable to the pure nitrogen. For stability reasons the inlet velocity was specified as 10 m/s instead the outlet velocity.

4 Results

4.1 Pipe

The first investigated geometry was the simplest one, a normal pipe with 30mm diameter and 100mm length. Using the symmetry it was modeled as a quarter model. Figure 1 shows the resulting velocity and temperature distribution in the pipe. It can be seen, that the velocity remains nearly constant over the length of the pipe. But the most interesting thing is that the temperature outside a boundary layer remains nearby the inlet temperature and the average temperature at the outlet is calculated to be at 458K. Therefore most of the air is too cold for melting thermoplastics and the temperature distribution in the outlet is very inhomogeneous.

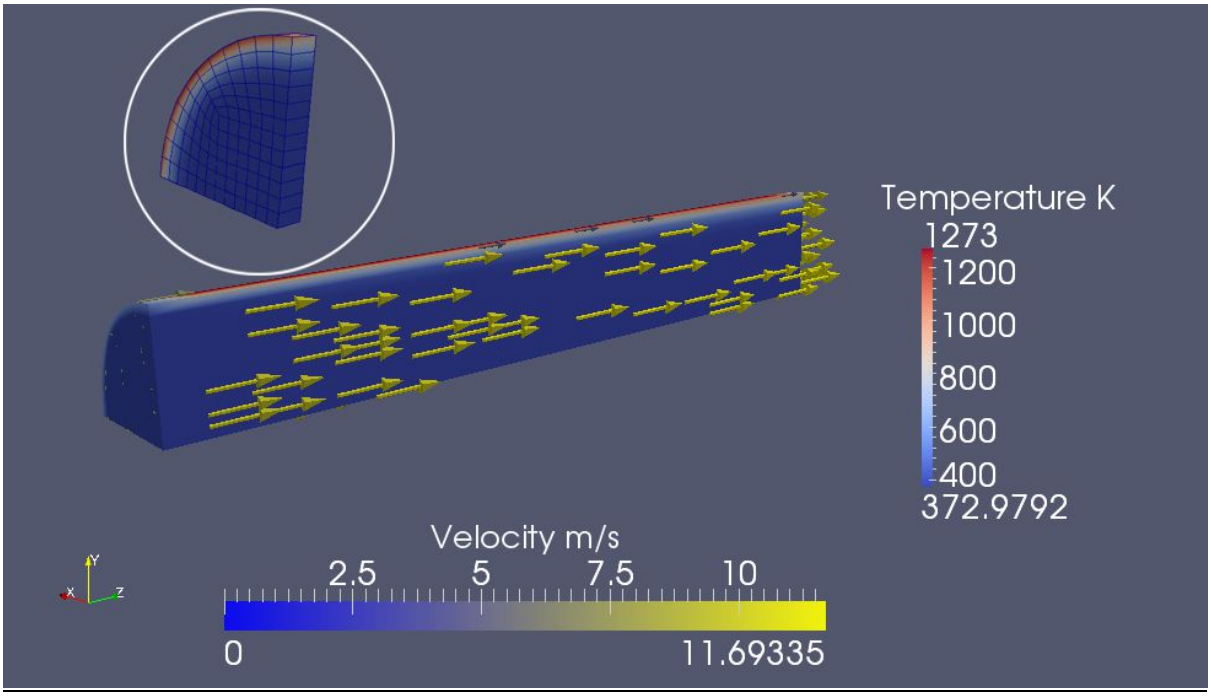

Figure 1: Temperature and Velocity distribution within the pipe-type hot gas torch. The detail in the white circle is a cross-section of the last elements at the outlet (The velocity is indicated with the arrows, whereas the temperature is shown through the color of the surface)**.**

4.2 Pipe with a core

As it was shown above, using a simple pipe is not successful. So a solution could be to bring in a heated core, in order to realize a two-side heating. This idea led to the second model, a doughnut- shaped flow cross section with a rectangular outlet. The core of this model was chosen to be 24mm in diameter, the outlet had a cross section of 5mm x 30 mm, and the rest of the geometry remained the same like the pipe (100mm length, 30mm diameter). This geometry and the used mesh are shown in Figure 2.

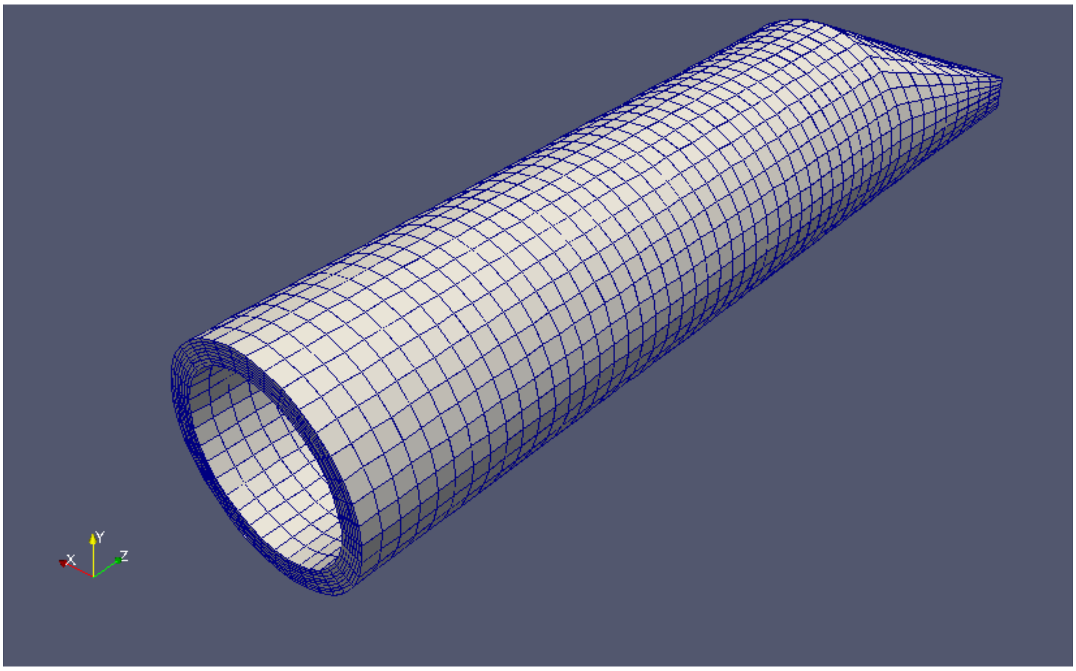

Figure 2: geometry and mesh of the pipe with a core.

The simulation with this model shows a quite high acceleration of the flow velocity, but a quite similar temperature profile to the simple pipe. Only the boundary layers of the flow show a high temperature, the centers of the flow is cold. This is shown in Figure 3. A closer look to the outlet in the x-z cross section (Figure 4) shows that this problem occurs not only in the height of the nozzle but also in the width. So a very wide spread temperature distribution, with an average temperature of 743K can be found. Also most of the volume flow occurs at the boundaries of the outlet.

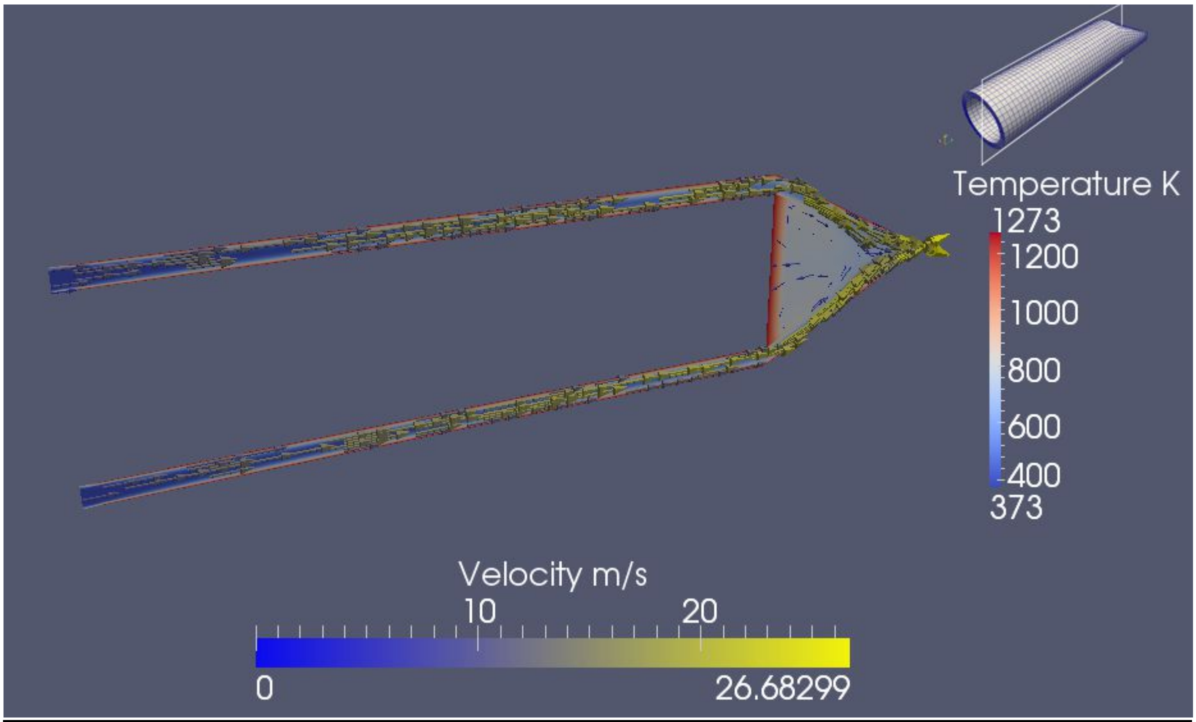

Figure 3: Temperature and velocity distribution in the y-z cross section of the pipe with core model (The velocity is indicated with the arrows, whereas the temperature is shown through the color of the surface).

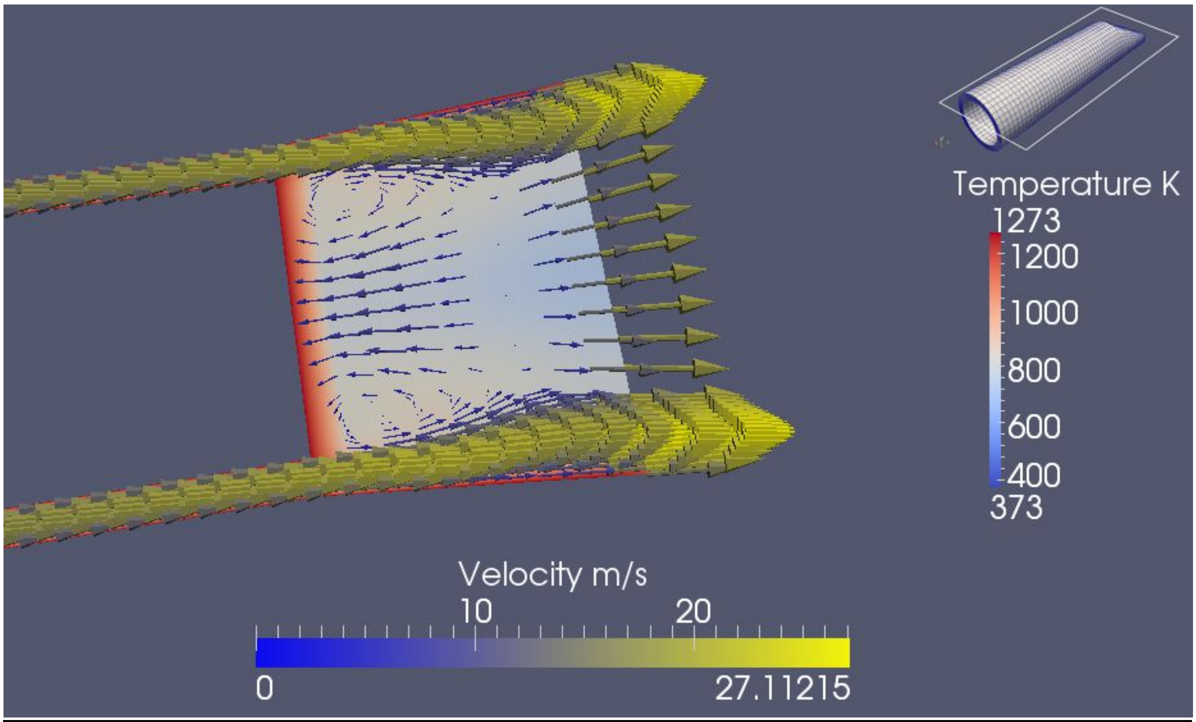

Figure 4: Temperature and velocity distribution in the x-z cross section of the outlet of the pipe with core model (The velocity is indicated with the arrows, whereas the temperature is shown through the color of the surface).

4.3 Helix type model

The required increase of the flow length and the heated surface under the constraint of maintaining a total length of 100mm led to another concept, the helix type model. It has a 12mm x 12mm cross section of the flow channel. Because of mesh generation problems within OpenFoam™, it was resigned to include a similar outlet as in the pipe with core model. It was only intended to see, if this type of torch provides sufficient heating power. The model and the mesh are shown in Figure 5.

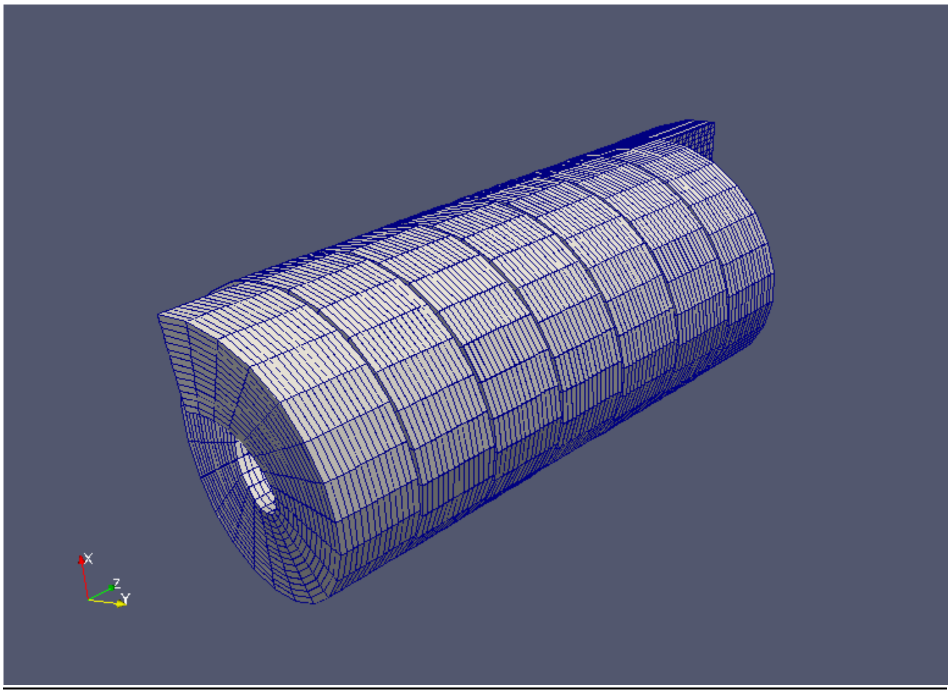

Figure 5: geometry and mesh of the helix type model.

Figure 6 shows, that the helix type model provides a similar velocity distribution to the pipe with core model, but a much better temperature distribution at the outlet. The detailed temperature distribution in the outlet is shown in Figure 7, where it can be seen, that the temperature difference between the boundary layer and the core of the flow is still up to 300K with an average temperature of 1043K. But the authors believe that this problem can be solved with one or two additional windings.

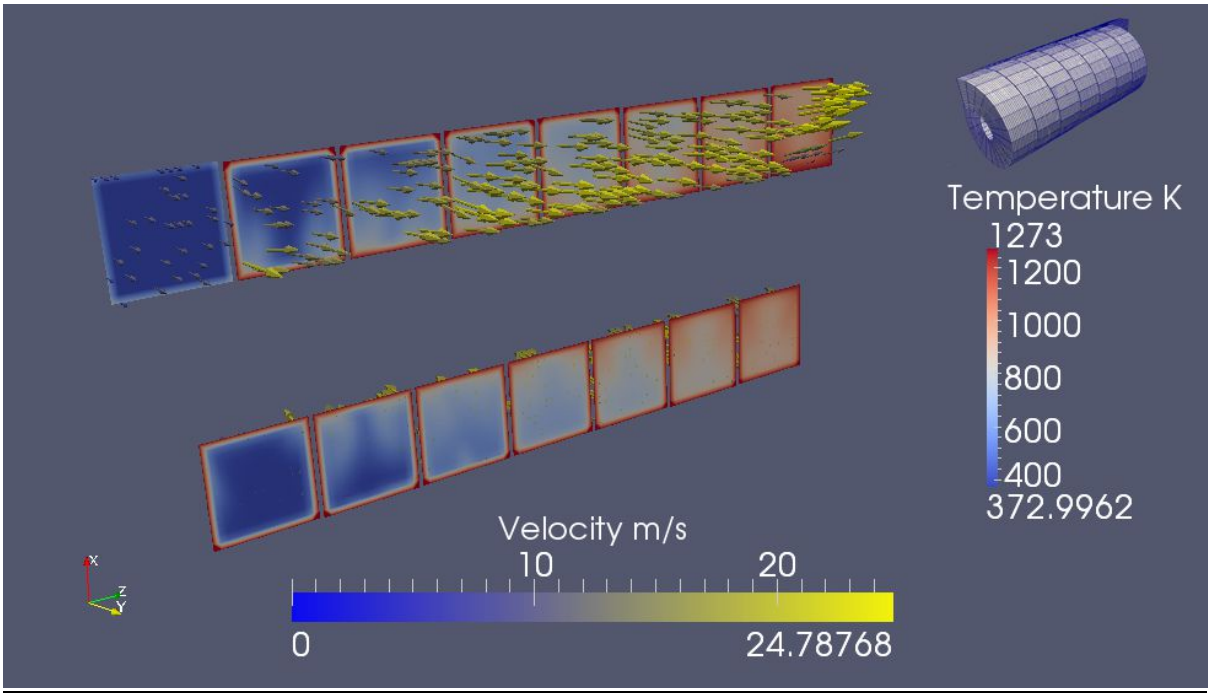

Figure 6: Temperature and velocity distribution of in the x-z cross section of the helix-type model. (The velocity is indicated with the arrows, whereas the temperature is shown through the color of the surface)

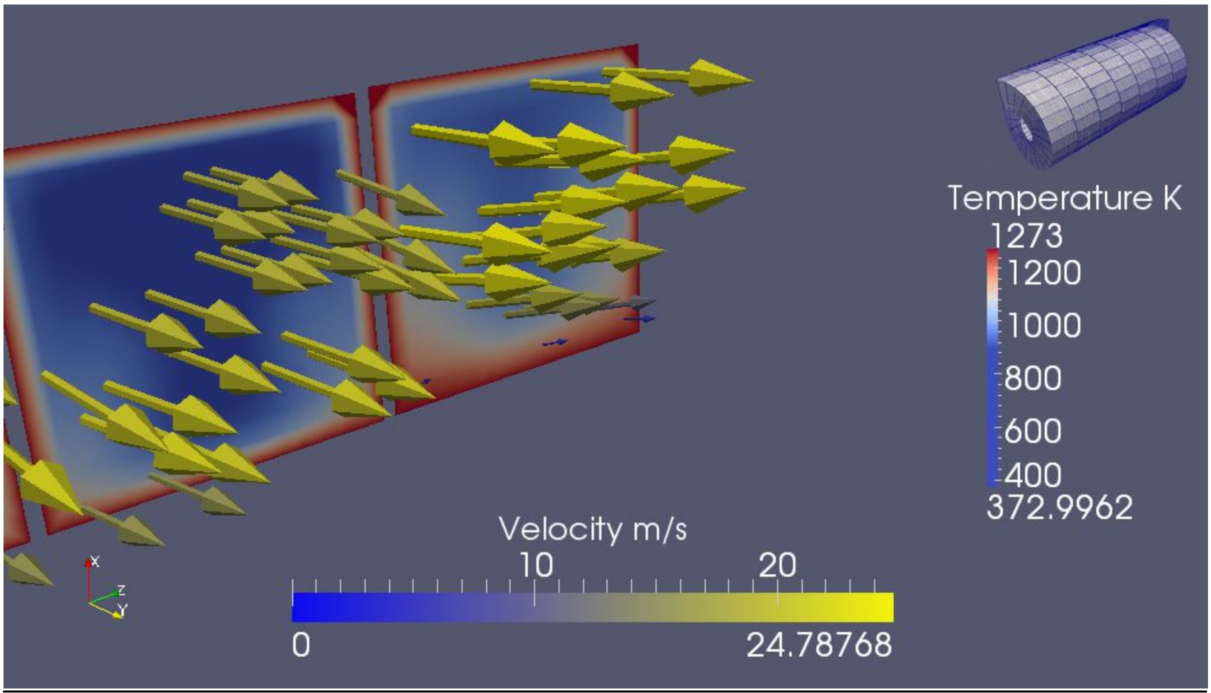

Figure 7: Detail of the temperature and velocity distribution of the helix-type model outlet. (The velocity is indicated with the arrows, whereas the temperature is shown through the color of the surface)

5 Summary and Outlook

The hot gas torch is a very attractive system for heating thermoplastic tapes within the tape placement process, because of its sufficient heating power and the reduced thermo-oxidative degradation risk. In this study CFD-simulations of three models of such a torch were performed, in order to gain data about the resulting velocity and temperature distributions at the outlet. The results of the simpler models, pipe and pipe with heated core, show very inhomogeneous temperature and velocity distributions, with large parts of the flow too cold to process thermoplastic tapes. A proper solution for this problem is the helix-type torch, which increases the flow length dramatically and therefore improves the heating of the flow. But it still needs to be optimized and further simulations with the real outlet have to be done. Also these results have to be validated experimentally and the simulations have to be extended to the free jet region and the heat transfer to the tape itself, because this is the real relevant information.

6 References

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