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Cost Efficient Solutions for Small Aircraft Development Processes Using Numerical Modelling Tools

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Summary

The aircraft design and development process is a specific area in engineering and has many methodologies available to help the engineers, designers nowadays. The fundamentals of the designing and sizing processes were laid down by Howe [1], Raymer [2], Roskam [3], Torenbeek [4], Fielding [5] and Stinton [6] among others. The authors presented guides and models are a compilation of proven methods, can be used in the design process of an aerospace vehicle. The main goal of their work is component sizing, vehicle configuration, propulsion, structural and systems layout, weight estimation, performance and stability evaluation methods along with the “softer” aspects of design such as cost, design development, manufacturing and operational aspects. Additionally to the general design methods, special methodologies have been carried out for aerospace vehicles with non-generic purposes by Hammond [7, 8], Griffin and French [9].

It is not a coincidence that an aircraft design and development processes are mostly handled confidentially by companies and kept in-house, since new methodologies are very expensive, mainly because they require a wide range of experimental inputs and data at the whole aircraft level. In the aerospace industry, it is essential to show compliance with the appropriate certification requirements, the applied design and development process must be capable, proven, safe and reproducible any time. But even if a company is in possession of the resources, demanded by the development process, the creation of an innovative, fundamentally new idea would be still a challenge. There is no exception in the validation process. Every company, especially the new and small ones, has to spend a tremendous amount of money to go through all the test procedures, the validation process requires. More established and larger companies can rely on their accumulated and available knowledge, which creates a significant market advantage.

Aerospace vehicle design and development has been the driving motor behind all computer aided engineering design methods. Eventually, the model-based development is a general concept in every field of the industry and innovation process. The applied methodologies are complex, thus only computer based calculations can be considered. A wide range of CAD/CAM software, FEA, and CFD analyses are available to support the work of engineers, and almost none of the aerospace design and development work, including the R&D processes, could

be carried out without applying the computational resources. However, at the same time, the model based development urges to create more and more complex methodologies, so however one can simulate the reality accurately, the computational demands increase exponentially. Meanwhile the designers, engineers have to face with the same expectations continuously: the structures must be lighter, have longer service life, the maintenance and repair have to be easy. Also, the power plants and other systems must improve their performance and efficiency, and provide more capability.

The limitation of harmful emissions and rising fuel prices generate further drivers. Many international projects have been dedicated to giving a solution for these problems, like the Horizon 2020 Clean Sky EU Framework program, which aims to reduce emissions of CO_2 and NO_x and perceived noise by 50%-80%-50% respectively by 2020 compared to the 2000 levels. Alternatively, the ESPOSA project developed with proven innovative technologies for aircraft, powered by small gas turbines up to ~1 MW. The goal was to deliver turboprop/turboshaft engines to the general aviation sector. The project included the engine related systems, to increase propulsion efficiency, safety and reduce pilot workload. Also, 10-14 % reduction was expected in the direct operating costs of a small aircraft. Another innovative idea was the GABRIEL Project, which was established to use a ground-based power to launch and recover aircraft, based on using a magnetic levitating pad. By cutting off the engine take-off thrust power, and removing the landing gear related components from the aircraft, the project predicted a considerably lower emission and noise near airports. National projects also target the reduction of emission gases by developing hybrid aircraft, for example, the Hungarian national supported EFOP-3.6.1-16-2016-00014 project titled „Investigation and development of the disruptive technologies for e-mobility and their integration into the engineering education".

It is a challenging task to decrease the direct operating emissions and costs while improving the system efficiency, manufacture, maintenance and disposal considering the complete lifecycle of the aircraft. It means more aspects have to be included in the design and development process, and additional activities have to be taken into account, like passenger complacency and hidden expectations. The additional drivers result in multi-dimensional, interdisciplinary, usually stochastic models. To simplify these models, designers/engineers need a tremendous amount of information to make their design choices, and this information nowadays is available at every point in the world by using only the world wide web. Recently, not the collection process, but the adaptation, filtering, and the management of these processes cause the real challenge. Besides storing, it is particularly important to keep the information database up-to-date.

These considerations have led to the appreciation of Knowledge Management, which has been realised by large and progressive companies, like NASA [10], Airbus [11] and Boeing [12]. Each one of them has developed roadmaps to record the processes and use the achieved know-how again. An excellent example is the Apollo program and its aftermath to demonstrate the importance of knowledge capturing. Shortly, the information in the modern world is widely available, but to efficiently collect, manage and reuse it is a significant challenge, something that companies are just beginning to solve.

Another driving factor is the globalisation, which makes possible for engineers/designers not to be confined to single workplaces, but could be a part of a worldwide organisation, even while working in home office. Companies apply time and knowledge sharing more frequently, utilising the time zone differences optimally they can implement almost non-stop development process. Indeed, to optimise this solution a well-established management is required in every field of the collaboration.

The aircraft design process has another specific field, which are the design environments. Without computer-aided development and automation processes, it is hard to imagine an aircraft manufacturer. Incipiently, to solve specific development and design issues, engineers and designers have developed their own codes. These codes mostly require significant, repetitive manual work and can provide only results in output tables, which require further interpretation. Later, following the evolution of different simulation tools by software developer companies, more accurate, complex, user friendly and highly automatized programs were available, and lead us to automate the whole chains of design processes. This way, it has become reachable to use such solutions in the different development phases, where it used to be inconceivable, like applying a CFD method in the early stage design processes. To apply these solutions, of course, these methods have to be simplified as much as it is possible since several problems require too high computational efforts for an early stage development phases.

As a matter of fact, the applied development process decisively influences the tools, engineers can use during their work. Two directions can be distinguished:

- Product-Based development: a set of tasks, processes and actions, which materialise the sales and services objectives of a company from the initial ideas to the products. Industries that produce a large number of products integrate the simulation processes with simulation tools and combine them in a beneficial way: when it is cheaper to break 10+ prototypes and carry out experimental-based development, companies are not investing into simulation tools, since it is just not worth the effort. The automotive industry, IT sector, light industry, etc. prefer to apply the product-based development.

  Project-Based development: this approach is mostly applied for high-volume developments, where the outcome of the investigation is limited number of products or the elaboration of a methodology can be applied later. The development process is strongly supported by simulation tools; sometimes it is the only applicable solution. Aerospace, naval architecture, railway industry (not considering the military developments here) mostly apply project-based development, since, the number of the manufactured product makes possibly to create only a limited number of prototypes. In these projects, it is essential to apply such simulation tools that can provide accurate results within a short time period, without utilising unnecessary computational efforts. The validation and certification of numerical methods are essential and urge engineers to generate newer, faster, more robust reliable methodologies, in order to decrease the development phase's time demand and its cost.

This thesis was dedicated to introducing the effect of the continuously expanding globalisation and the opportunities, provided by the crowdsourcing, and furthermore to dig into three different time-consuming fluid-mechanic problems, and suggest relevantly shorter, but still accurate solutions. The connection between these investigation fields that all of them occur in a development process, furthermore 3 of them have been already applied in an international research project. The considered problems are the following:

1. The effect of a turboprop to the aircraft structure and its components' aerodynamic behaviour has been published by several scientists and engineers. The innovation, introduced in this thesis, is to implement the Schmitz method and use it as an Actuator Disk Model. Axial and tangential momentum sources have been set to simulate the effect of the propeller. Also,

the total pressure values with including induced velocities, flow directions and static temperatures have been used as inlet boundary conditions at the downstream plane of the propeller. In this way, the computation time demand can be ten times shorter than using the conventional Rotating domain model, but the effect of an object downstream of the propeller blades (like engine nacelle) is taken into consideration. In this way, the advantages of the Actuator Disk Model and Rotating domain model are united.

2. Although the conventional way to analyse and design engine air intake of a small aircraft is to perform cost-demanding experimental studies, recently CFD software provide an opportunity to simulate the trajectories of different type of particles, such as hailstones, dust, or even liquid water droplets. The thesis summarises and reviews the available modelling technics, and comparing the effect of different parameters, meanwhile suggests reliable solutions, which can be applied for engine intake design, improvements and optimisation.

3. The one of the most widespread equipment used in aerospace industry are the heat exchangers. However, because of their complex internal geometry, usually to simulate the flow conditions inside them is time and cost demanding process. A simple and cost-effective method is introduced in the present thesis, which can simulate the heat exchanger caused pressure drop and heat transfer to the cooling (ambient) airflow accurately without using the detailed geometry of the assembly. Porous media is applied for the heat exchanger, which's parameters (loss and permeability coefficients) are calculated by applying Darcy's law. The density dependent loss coefficient is taken into consideration by user defined function in the applied software. The heat transfer processes have been modelled with inserting source term in the energy conservation law of the porous media.

At first sight, these problems could seem to be independent, but each one of them belongs to a complex flow simulation process of a turboprop aircraft: the airflow is accelerated by the propeller blades, which generate the thrust, downstream of the propellers the air enters to the air intake duct of the engine, where a particle separator device takes place. Or it can flow away along the engine nacelle, generating aerodynamic drag. Some part of the external airflow can also be used as a ram air inlet in a plate-fin type heat exchanger, which is responsible for decreasing the temperature of the lubricant oil. The all mentioned fluid dynamic problems are shown together in Figure 1.

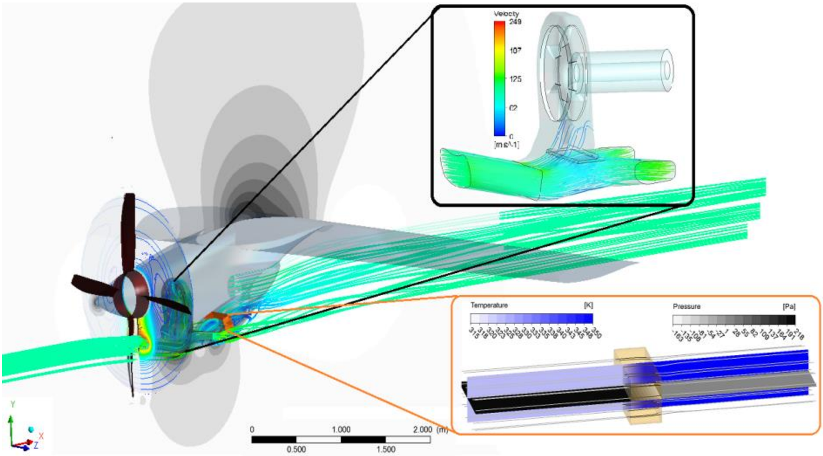

Figure 1: Illustration of the coherence between the investigated topics of this thesis

Depending on what kind of method is used, the computational requirements and accuracy can vary in a wide range. To compare the computational efforts of different Reynolds Averaged Navier Stokes equations-based CFD simulations the *CFD Worthiness Number* ($W_{CFD,i}$) has been carried out, which consists of predictably parameters and gives a dimensionless number to demonstrate the effort-requirement of different methods.

In most cases the CFD Worthiness Number varies between 10 and 45, to reach lower or higher values extreme simulation cases are required. The applicable region is below 20, where if it was closer lower than 15, the computational requirements are minimal (a notebook or ultrabook can handle the simulation), while if $15 \leqq W_{CFD} \leqq 20$, it needs a stronger Personal Computer (PC). Over 20, the simulation needs a high-performance workstation and also it has significant time demand. So, these problems should be taken into consideration in R&D problems, but for small aerospace companies during development it generally not worth to apply.

Depending on this dimensionless number, the introduced CFD methods have been compared to each other, as Table 1 shows. Of course, only a few examples have been collected and presented due to the large amount of data.

	RDM	*ADMv1*	*ADMv2*	*ADMv3*	*HX with porous media*	*HX with detailed mesh*	*Particle tracking*
N_m	1.91*10^7	1.61E*10^7	1.61*10^7	1.34*10^7	5.35*10^7	4.60*10^7	1.16*10^7
N_m^e	7	7	7	7	5	10	7
N_m^s	1.9065034	1.6054875	1.6054875	1.34286	5.34591	4.5974826	1.1557515
N_{it}	3500	200	200	200	50	500	250
β_g	1.05	1.05	1.05	1.05	0.9	1	1.1
ϵ_i	0.045	0.063	0.044	0.029	0.016	0.03	0.05
n_c	4	4	4	4	4	4	4
ω_p	3600	3600	3600	3600	3600	3600	3600
ψ_p	2.4	2.4	2.4	2.4	2.4	2.4	2.4
$W_{CFD,i}$	28.1	20.7	19.5	18.0	12.0	35.4	19.7

Table 1: Examples for CFD Worthiness Number values based on the introduced CFD simulations cases

New Scientific Results

I have completed knowledge-management and Computational Fluid Dynamics based researches for improving the effectivity of small and medium sized aerospace companies, and the theses are presented as follows:

Thesis 1:

The conventional 3rd generation innovation process has to be redesigned in order to meet with the demands of small aerospace companies and their suppliers with reduced innovation capabilities. (The flow chart about the innovation model is found in Figure 2.)

1.1. *The proposed innovation model is based on the idea generation, which applies 6th generation open funnel model to select the useful and efficient ideas and integrates knowledge management. The idea generation have to be supported by crowd sourcing, knowledge sharing and the conventional scientific breakthroughs, new technologies.*

1.2. *The model considers the crowd as potential option for participating in innovation processes by means of knowledge sharing, freelancer engineers and financial stakeholders, rather than to be simple customer.*

1.3. *The cost of a development process is optimised by involving outsider participants in the idea generation, development process and by outsourcing the marketing and sales.*

1.4. *To meet with the strict rules of aerospace industry, "state-gates" must be applied as feedbacks and drivers in the process. While the idea generation and development phase is carried out as a quasi-open innovation process, actually the company has responsible, so the closed innovation processes are also combined.*

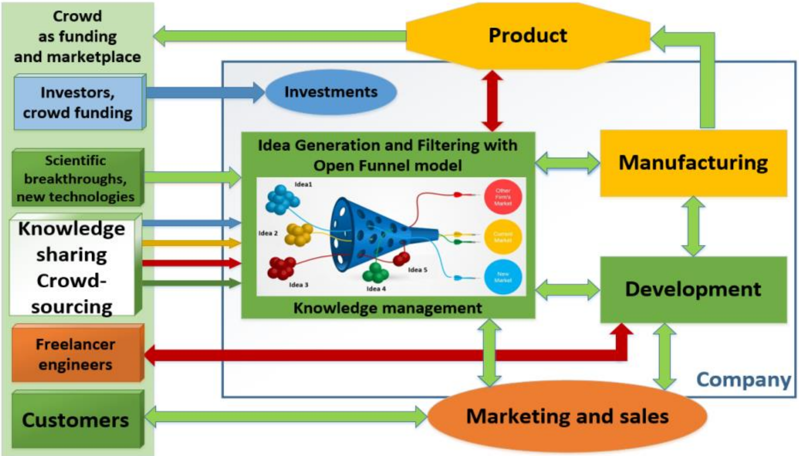

Figure 2. Crowdsourcing supported 3rd generation innovation model addressed for small aerospace company's innovation and development

Related publications: [13-19]

Thesis 2:

To compare different RANS based CFD methods' effort requirement, the presently developed and below described dimensionless CFD Worthiness Number ($W_{CFD,i}$) can be used, which incorporates the mesh cell number of the investigated model given in normal form, resolved to the significant part (N_m^s) and to the exponent (N_m^e), the iteration number (N_{it}), which is necessary to reach the convergence criteria, a correction factor (β_g) to take into account the quality of the mesh, the processor performance factor (ψ_p) and finally the accuracy (ϵ_i), which is given by the average relative error for the investigated model parameter (the π is a weight function in the equation):

$$W_{CFD,i} = \frac{N_m^e}{\psi_p} * ln\left(N_m^s * \beta_g * N_{it}\right) * e^{\pi \epsilon_i}.$$

2.1. The processor performance factor must be calculated as follow:

$$\psi_p = \omega_f * \sqrt{n_c} = \frac{\omega_p\ [MHz]}{3000\ [MHz]} * \sqrt{n_c},$$

where ω_f is the processor's frequency ratio, which is a ratio of the applied computer's processor (ω_p) to a baseline 3000 MHz basic processor frequency; and n_c is the number of useable cores.

2.2. The correction factor (β_g) is responsible to take into consideration the quality of the mesh, and it has to be the following values:

Mesh quality	$\boldsymbol{\beta_g}$ [−]
Simple, hexa mesh	0.9
Complex, structured hexa mesh with boundary layers and minimal poor elements	0.95
Simple mesh made from tetra elements	1
Complex mesh, made from tetra cells, with minimal poor elements and boundary layers	1.1
Simple, hybrid mesh	1.05
Complex hybrid mesh with minimal poor elements and boundary layers	1.15

2.3. For small companies with limited resources both in man-hours, in experience or knowledge and in computational infrastructure, the CFD Worthiness Number for an applied simulation technic have to be lower than 20:

$$W_{CFD,i} \leqq 20$$

Furthermore, simulation cases with CFD Worthiness Number between 10 and 15 are suitable for applying them in optimisation methods.

Related publications: [20]

Thesis 3:

For computational cost reduction purpose, RANS based CFD simulation of small and medium sized, propeller driven aircraft operating in $M \leq 0.35$ speed range, the effect of the rotor have to be taken into consideration by applying the Schmitz method in order to achieve the desired CFD Worthiness Number.

3.1. *The geometry of the propeller has to be replaced with a cylinder cavity, divided to equally thick (Δr=const.) rings. The need for modelling the actual rotor geometry and fine meshing can be spared by this way. The rings have to be filled with fluid domain, connecting to the rest of the airflow by general interfaces. The effect of the propeller is taken into consideration with applying sources terms.*

3.2. *The Schmitz method (combined Blade Element and Momentum Theory) have to be used, which provides the source terms in each ring, as it is described by the following equations:*

i. $dT = 2\pi r dr (V + v) 2\rho v$,
ii. $dQ = 2\pi r dr (V + v) 2\rho u$,
iii. $dV = 2\pi r dr x_{disc}$

where, V marks the flight speed, v and u are the axial and tangential induced velocities, dT and dQ are the elementary axial and tangential components of the resultant force, x_{disc} is the thickness of the rotor, finally r is the radius and dr is the elementary radius.

The change of Turbulence Kinetic Energy downstream of the rotor can take into consideration with a source term in each ring (r_i), determined by the results of the Schmitz method as follows:

iv. $k = \frac{1}{2} V'^2$, *where* $V' = u_i = f(r_i)$

u_i is the resultant induced velocity: $u_i = \sqrt{u^2 + v^2}$.

2.3. *To optimise the engine nacelle downstream of the propeller in a stationer flight phase, the history of the airflow before the propeller is indifferent. Thus, by neglecting the propeller domain, the induced velocities have to be considered as total pressure increment in the propeller downstream surface,* *calculated by the Schmitz method. The inlet boundary conditions are the next:*

v. $p_{total} = p + \frac{\rho}{2}[(2v + V)^2 + (2u)^2],$

vi. $n_r(r) = \frac{u(r)\,sin(\theta)}{\sqrt{u^2(r)+(v(r)+V)^2}};\; n_z(r) = \frac{v(r)+V}{\sqrt{u^2(r)+(v(r)+V)^2}}$

vii. $T = T_{farfield}$

where p is the static pressure, ρ is density, T stands for static temperature. n_r and n_z are the unity directional vectors in the (r, θ, z) cylindrical coordinate system.

Related publications: [21-24]
Related scientific reports: [25-28]

Thesis 4:

In a RANS based CFD simulation of a small aircraft engine intake channel, with especial care for the behaviour of different particles, in order to create a base simulation for an optimisation with lower CFD Worthiness Number than 20, the collected and proposed physical effects, model, approaches and considerations have to be used.

4.1. Two-way coupled solutions have to be used with homogenous, spherical-shaped particles, which quantities and diameters depend on the international regulations: 20 µm and 2.66 mm water droplets, 1 mm ice crystals and 16 mm hailstones.

4.2. The wall roughness have to be neglected according to the relatively large particle sizes, but the high Reynolds Number requires the Schiller-Naumann drag force.

4.3. In the case of 2.66 mm water droplets, the Weber number is much higher than the critical Weber number, thus the particle break-up model has to be applied. The smaller, 20 µm water droplets on the other hand are affected by the turbulent dispersion force, so it must be considered.

4.4. In every case, the particle collision has to be simulated by applying Sommerfeld model:

- *the coefficient of restitution is 1 (fully elastic collision) when considering the collision of solid ice particles with each other, while it is 0.1 in the case of interaction between fluid particles,*
- *the coefficient of restitution is 1 (fully elastic collision) when considering the collision of solid ice particles with walls, while it is 0 in the case of interaction between fluid particles and walls.*

Related publications: [24, 29]
Related scientific reports: [30-32]

Thesis 5:

To investigate the effect of an oil-to-air heat exchanger on the small airplane's aerodynamic characteristics, with special regard to the drag, the best CFD Worthiness Value (between 10 and 15) can be obtained by implementing a RANS based CFD simulation applying porous media and the model has to be the following specifications:

5.1. *True velocity model is applied, for which the volume porosity have to be determined as the ratio of the available (reduced) and the full cross section of the heat exchanger as follows:*

$$\gamma = \frac{A_{reduced}}{A_{full}}$$

5.2. *By applying Darcy's law, using the heat exchanger's supplier characteristics, the quadratic (A) and linear (B) coefficients have to be calculated and the quadratic loss (K_{loss}) coefficients and the permeability (K_{perm}) of the porous media have to be calculated as follows:*

$$K_{perm} = \frac{\mu L}{B} \quad and \quad K_{loss} = \frac{2A}{L\rho_i}$$

where μ is dynamic viscosity, L stands for the length of the heat exchanger and ρ_i is the density of the fluid.

5.3. *If the loss coefficient from the previous equation is temperature dependent, the accuracy of the simulation can be increased by 3 % in case of using temperature dependent density ($\rho_i(T)$).*

5.4. *Volumetric energy source have to be used for modelling the heat transfer processes between the heat exchanger and cooling air.*

Related publications: [23]
Related scientific reports: [25, 26]
Indirectly related publications: [33-35]

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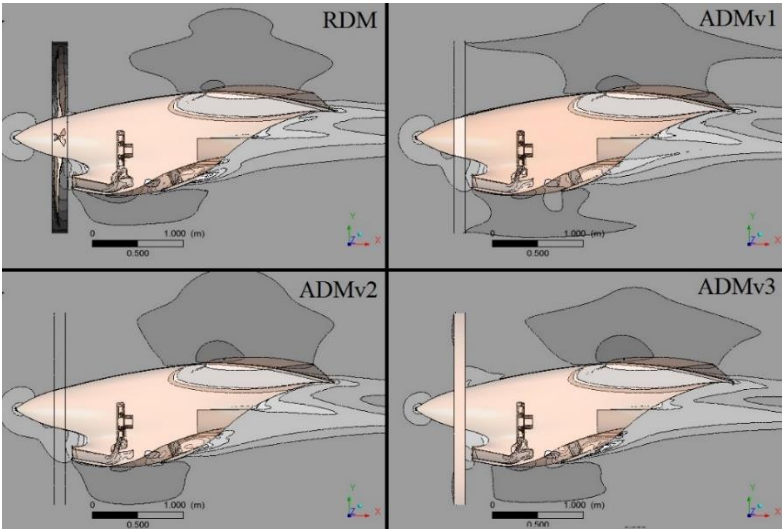
RDM
ADMv1
ADMv2
ADMv3
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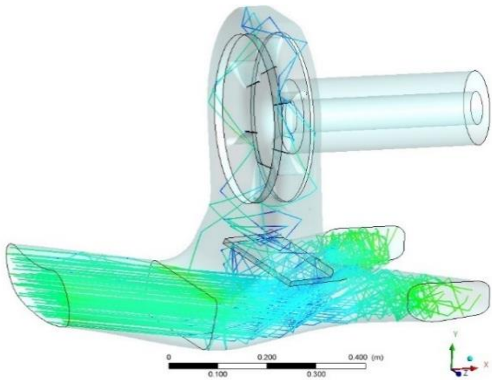
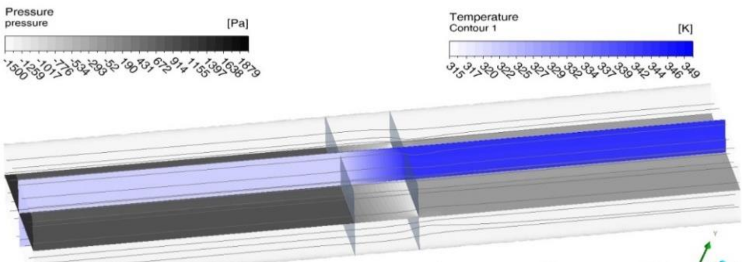
0.500


0
0.200
0.400 (m)
0.100
0.300


Pressure
pressure
[Pa]
-1500 -1259 -1017 -776 -534 -293 -52 190 431 672 914 1155 1397 1638 1879
Temperature
Contour 1
[K]
315 317 320 322 325 327 329 332 334 337 339 342 344 346 349
0
0.200
0.400 (m)
0.100
0.300