Enhanced Turbomachinery Capabilities for Foam-Extend: Development and Validation

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Abstract Turbomachinery simulations represent one of the most challenging fields in Computational Fluid Dynamics (CFD). In recent years, the general CFD capabilities of foam-extend have been extended by introducing and maintaining additional features specifically needed for turbomachinery applications, with the aim of offering a high-quality CFD tool for the study of rotating machinery. This work presents the implementation and validation of new capabilities for turbomachinery with foam-extend, a community-driven fork of OpenFOAM®. The formulation of an energy equation more convenient for compressible turbomachinery applications has resulted in the rothalpy equation. Rothalpy is a physical quantity conserved over a blade row, stator or rotor, but not over a stage, both stator and rotor. It is fundamental to take into account that the value of rothalpy is not continuous across the rotor–stator interface, due to the change of rotational speed between zones. The rothalpy equation has been derived for both relative and absolute frames of reference, showing that additional terms appear in the absolute frame of reference. Moreover, additional functionality has been added to the rotor–stator interface boundary conditions' General Grid Interface (GGI), partial Overlap GGI and Mixing Plane Interface, in order to account for the rothalpy jump. The development of these new capabilities and their validation are shown, as well as industrial applications of compressible turbomachinery flows.

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Nomenclature

e	Energy
h_0	Total enthalpy
i	Rothalpy
ρ	Density
p	Static pressure
R	Radius
S_H	Source term of enthalpy
T	Temperature
t	Time
$\bar{\bar{\tau}}$	Viscous stress tensor
$\mathbf{U}$	Rotational velocity vector
$\mathbf{V}$	Absolute velocity vector
V_θ	Component of absolute velocity in the tangential direction
$\mathbf{W}$	Relative velocity vector
ω	Rotor angular velocity

1 Introduction

The role of turbomachinery studies is fundamental, nowadays, in a large number of industrial CFD applications. Rotating machinery presents particular challenges, such as complex geometries, the presence of an adverse pressure gradient and the relative motion of multiple rotors and stators, which require the modification of standard CFD tools with turbomachinery-specific capabilities. Jasak and Beaudoin [1] have described the implementation of turbo-specific features in the open-source numerical simulation software foam-extend, emphasizing the basic functionalities of turbo tools, the software layout in foam-extend and the numerical formulation of interfaces between stages.

The Open-Source platform foam-extend is a community-driven fork of OpenFOAM®, consisting of C++ libraries for Computational Continuum Mechanics, with extended CFD capabilities. The object-oriented architecture of foam-extend allows users to efficiently modify specific libraries and take advantage of the existing parts of the toolbox. The full source code of foam-extend is released under the GPL license and can be used at no cost.

The main challenges that turbomachinery simulations impose are linked to the need to study the relative motion of multiple rotors and stators. Depending on the transient or steady-state approach, the rotation can be handled in two ways: directly, by moving the mesh, or indirectly, by using a static mesh and modifying the equations to take into account the rotation. The former is only appropriate for transient simulations, whereas the latter is suitable for steady flow and may be formulated either for a single body in rotation, using the Single Rotating Frame of Reference method (SRF), or for different rotating regions, using the Multiple Rotating Frame of Reference method (MRF). SFR and MRF can be implemented choosing either the absolute or relative velocity formulation. Recently, a new method for studying turbomachinery has also been developed and validated in foam-extend: the Harmonic Balance method for nonlinear, temporally periodic and incompressible flows [2].

The interface between stationary and rotating parts can be treated in several ways: for transient simulations with topological changes, the sliding mesh technique is commonly used, whereas for steady-state simulations, the methods available are the General Grid Interface (GGI), in which a weighted interpolation is performed to evaluate and transmit flow values across a pair of conformal or non-conformal coupled patches [3]; the partial Overlap GGI for cases in which some of the interface faces are not physically covered by their counterpart; and the Mixing Plane Interface, which consists of circumferential averaging of the solution at the rotor–stator interface [4].

The focus of this paper is the implementation of the rothalpy equation in foam-extend, as well as the implementation of the related boundary conditions and rotor–stator interfaces in order to properly handle this physical quantity. The validation is performed on steady simulations, in which the mesh is static and the rotation is handled by means of the MRF approach.

The paper is organized as follows: Sect. 2 contains a theoretical discussion of the mathematical model, Sect. 3 reports the validation cases and discussion, ending with the conclusion in Sect. 4.

2 Mathematical Model

The energy equation recommended for complex turbomachinery applications are the conservation of rothalpy equation. This is due to the rothalpy's property of being conserved over a blade row, stator or rotor, under the conditions investigated by Lyman [5]: isentropic flow, steadiness in the rotor frame, constant rotor angular velocity and no work done by the net viscous and body forces on the relative flow.

The rothalpy is a physical quantity, defined as [6]

$$i = h_0 - \omega R V_\theta. \tag{1}$$

The steady conservation equation for rothalpy is strictly dependent on the MRF formulation used. When the MRF is formulated in relative velocity, it is

$$\nabla\cdot(\rho i \mathbf{W}) = \nabla\cdot(k \nabla T + \bar{\bar{\tau}} \cdot \mathbf{V}) + S_H. \tag{2}$$

When the absolute velocity formulation is used for MRF, the steady conservation equation for rothalpy is

$$\nabla\cdot(\rho i \mathbf{W}) = -\nabla\cdot(\rho \omega R V_\theta \mathbf{W}) - \nabla\cdot(p \mathbf{U}) + \nabla\cdot(k \nabla T + \bar{\bar{\tau}} \cdot \mathbf{V}) + S_H. \tag{3}$$

Equations 2 and 3 differ because of the two terms $-\nabla\bullet(\rho\omega R V_\theta \mathbf{W})$ and $-\nabla\bullet(p\mathbf{U})$, which are only present in Eq. 3. These are, respectively, the convection of the quantity $\omega R V_\theta$ and the work done by the pressure forces. At the rotor–stator interfaces, the value of the rothalpy is not equal on both the rotor and stator sides, as the rotational velocity of the stator is zero. This requires modifications of existing rotor–stator interface methods: GGI, partial Overlap GGI and Mixing Plane Interface, in order to take into account the rothalpy jump at the rotor–stator interface. The value of the jump has been calculated by observing that on the stator, the rothalpy is equal to total enthalpy, being the angular velocity of rotor null, whereas on the rotor, both components of the rothalpy are non-null.

$$\begin{cases} i = h_0 & \text{stator} \\ i = h_0 - \omega R V_\theta & \text{rotor} \end{cases} \tag{4}$$

Therefore, the value of the rothalpy jump at the rotor–stator interface is $-\omega R V_\theta$. Accounting for the possibility of reverse flow, the jump has to be added to each face where the flux is going from the stator to the rotor and has to be subtracted from each face where the flux is going from the rotor to the stator.

3 Validation and Discussion

Validation of the new compressible solver specialized for turbomachinery applications has been carried out comparing the global turbomachinery parameters and the flow fields achieved with foam-extend and with a CFD commercial solver.

A 1.5-stage axial turbine has been chosen as the validation case. Steady simulations have been performed, accounting for only one rotor position. In order to shorten the CPU time, periodic boundary conditions have been adopted and only 1 blade passage has been simulated, with whole geometry having 36 blades in each rotor and stator. The mesh used is structured and consists of 405,600 hexahedral cells. The rotational speed is set to 3501 rpm and the inlet velocity is 60 m/s, with the kinematic viscosity being 1.8×10^{-5} m^2/s. The interaction between the rotor and stator has been resolved by taking advantage of the new implemented boundary conditions, which handle the rothalpy jump over the rotor–stator interfaces. At the rotor–stator interfaces, all of the variables are transported continuously, except for rothalpy.

In this work, two different methodologies of interface treatment have been considered: the partial Overlap GGI and Mixing Plane approaches.

3.1 Aachen Test Case: Partial Overlap GGI Approach

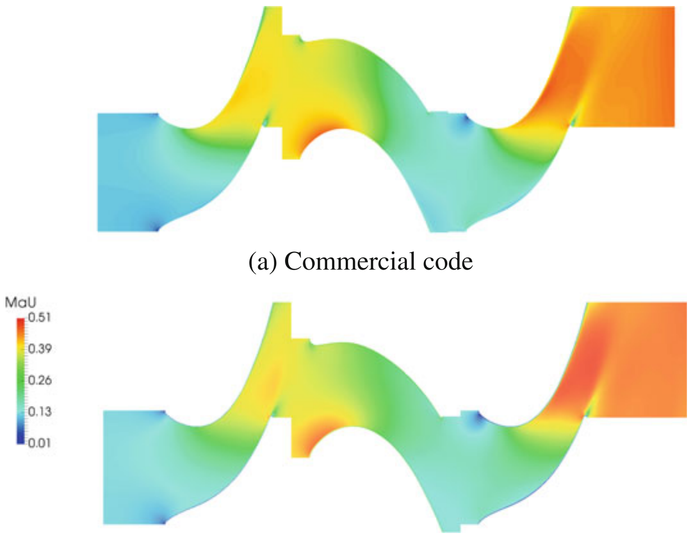
First, the partial Overlap GGI approach has been used at the rotor–stator interfaces. It interpolates the variables from one interface patch to another, allowing the use of a non-conformal mesh and the implementation of jump conditions over the interface before the interpolation is effected.

In Fig. 1, a comparison of the Mach number field obtained with a commercial code and the one obtained with foam-extend is shown. It can be noticed that the Mach number is continuous over the interface in both cases, and that the stator and rotor wakes are successfully resolved using the rothalpy jump boundary condition.

Figure 2 shows the static pressure fields comparison, whereas the temperature fields can be seen in Fig. 3. Since the temperature is calculated from the rothalpy, the effect of the rothalpy jump can be observed, as the temperature is continuous over the interface, rather than showing a jump.

3.2 Aachen Test Case: Mixing Plane Approach

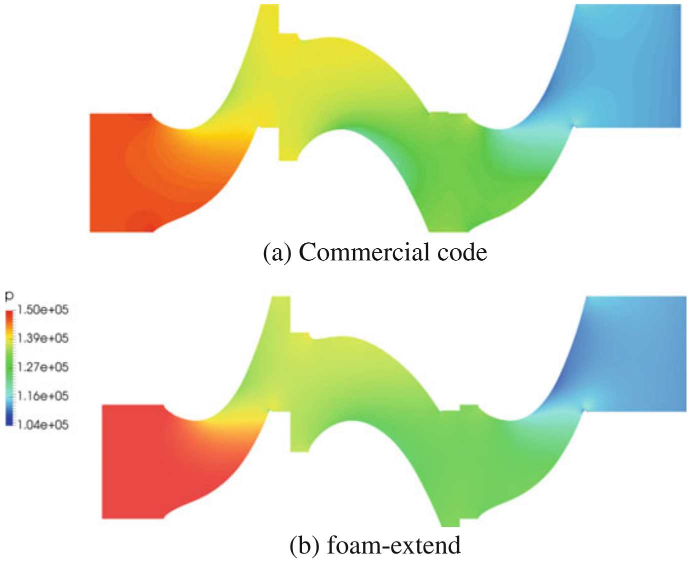
The Mixing Plane approach is usually employed when rotor–stator interaction is not of primary importance, but temporally averaged flow fields are considered. The flow fields calculated using the Mixing Plane Interface are comparable to those obtained by averaging the solution achieved in the transient simulation over time.



(a) Commercial code

(b) foam-extend

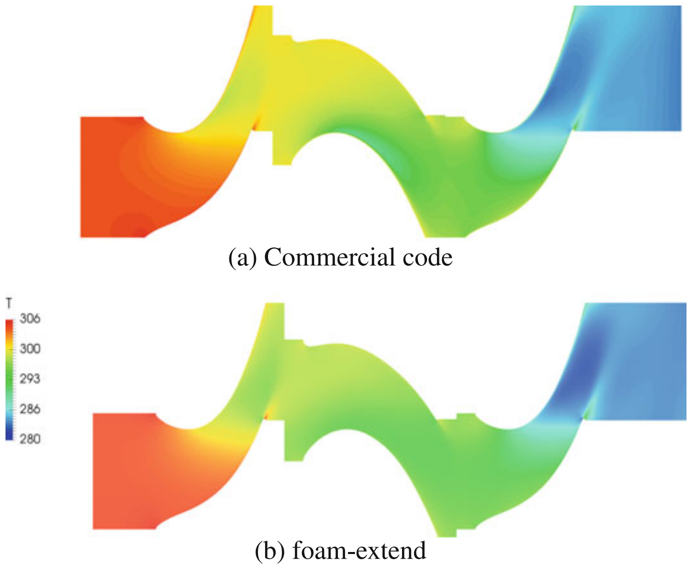
Fig. 1 Mach number field comparison



(a) Commercial code

(b) foam-extend

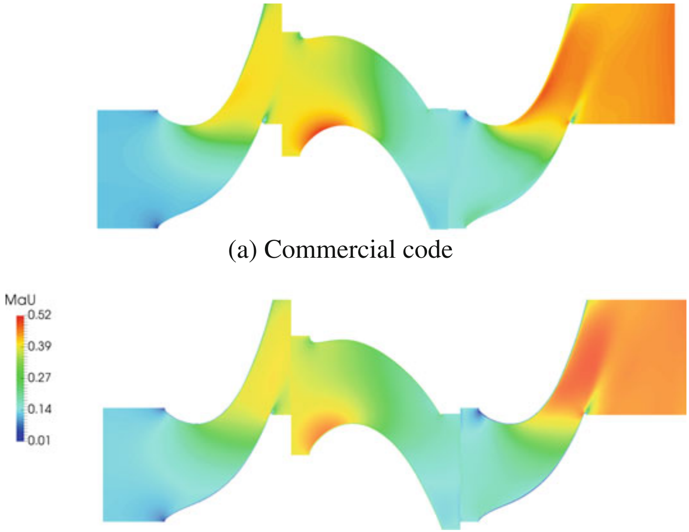
Fig. 2 Static pressure field comparison



(a) Commercial code

(b) foam-extend

Fig. 3 Temperature field comparison



(a) Commercial code

(b) foam-extend

Fig. 4 Mach number field comparison

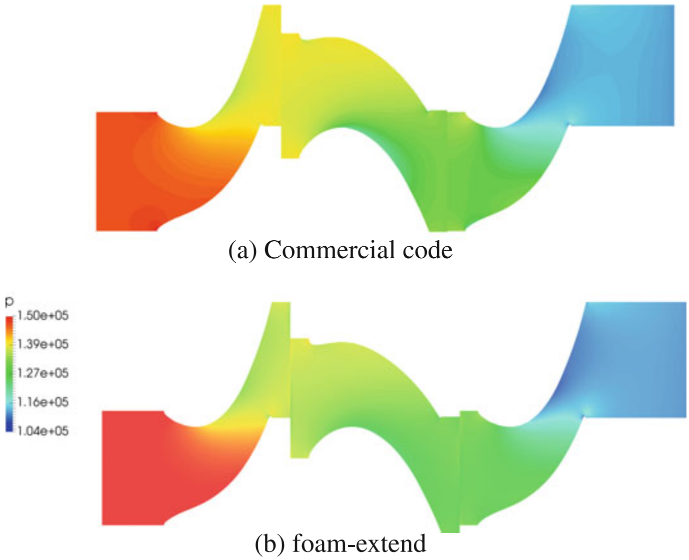
Figure 4 presents a comparison of the Mach number field achieved with a commercial software and the one achieved with foam-extend by using the Mixing Plane approach at the rotor–stator interfaces.

Compared to the partial Overlap GGI approach, the interfaces are visible in this case due to the fact that the flow field has been averaged before being passed to the opposite side of the interface. By doing this, the variables are no longer continuous, but the result can still be considered physical, as it resembles the temporally averaged solution. It should be noted that, regardless of rothalpy jump, the mass conservation over the Mixing Plane Interface is preserved. Mass flow relative differences between the rotor and stator interfaces are on the order of $10^{-3}\%$.

Figures 5 and 6, respectively, present the static pressure and temperature fields.

3.3 Global Pump Parameters Comparison

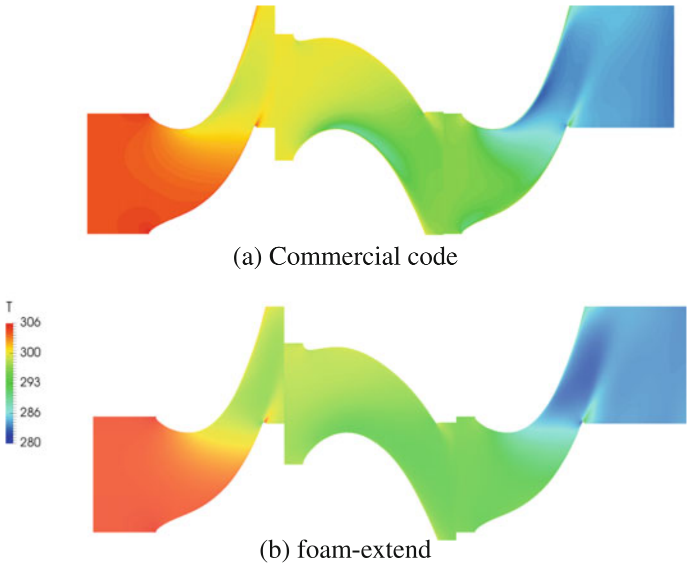
The global pump parameters of isentropic efficiency and torque related to the first stage are presented in Table 1. Two different approaches of interface treatment, partial Overlap GGI and Mixing Plane Interface, and two CFD softwares, foam-extend and a commercial code, have been employed in this study. The last column presents the differences between the two codes, while the third row presents the differences between the two approaches. The differences comparing the approaches are below 1%, showing that, in the case of steady-state simulations, the Mixing Plane approach



(a) Commercial code

(b) foam-extend

Fig. 5 Static pressure field comparison



(a) Commercial code

(b) foam-extend

Fig. 6 Temperature field comparison

Table 1 Global pump parameters comparison

		Foam-extend	Commercial code	Difference (%)
Isentropic efficiency (–)	Partial Overlap GGI	0.8405	0.8553	1.78
	Mixing plane interface	0.8435	0.8499	0.76
	Difference (%)	0.37	0.63	
Torque (N/m)	partial Overlap GGI	5.2343	5.2428	0.16
	Mixing plane interface	5.2176	5.1986	0.36
	Difference (%)	0.32	0.84	

can be used as an accurate alternative to partial Overlap GGI if rotor–stator interaction is not needed. This is especially significant for cases with different pitches between the rotor and stator rows, as partial Overlap GGI is not suitable for this application. Comparing the results between foam-extend and the commercial code, the highest error is 1.78%, while other errors are below 1%.

Being an important aspect in turbomachinery simulations and design, efficiency differences show that foam-extend's rothalpy approach gives results comparable to a commercial CFD software.

4 Conclusion

In this work, the implementation and validation of additional turbomachinery functionality in foam-extend have been presented. The energy equation has been solved for the physical quantity rothalpy, which is convenient for turbomachinery applications, as it is conserved over a blade row, stator or rotor. The use of rothalpy has required the implementation of specialized boundary conditions for treating the rothalpy jump over the rotor–stator interface in order to obtain a continuous temperature field. The jump occurs due to rothalpy taking into account the rotational velocity, which is null for the stator. Regardless of the interface treatment chosen, partial Overlap GGI or Mixing Plane Interface, the rothalpy jump is performed in the interpolation part of interface communication. For validation, a 1.5-stage axial turbine has been used and the results achieved with foam-extend and with a commercial CFD software have been compared, showing good agreement. Foam-extend can, therefore, be efficiently used as a part of the development process with full turbomachinery capabilities.

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Appendix

The MRF may be formulated using the relative or the absolute velocity formulation. In the first case, the conservation of rothalpy in a moving reference frame is derived directly from the conservation of energy formulated in terms of relative internal energy. It is

$$\frac{\partial(\rho i)}{\partial t} + \nabla\mathbf{.}(\rho i \mathbf{W}) = \frac{\partial p}{\partial t} + \nabla\mathbf{.}(k\nabla T + \bar{\bar{\tau}} \cdot \mathbf{V}) + S_H. \tag{5}$$

When the absolute formulation is used for the MRF, the conservation of rothalpy equations for a steadily moving frame is

$$\begin{aligned}\frac{\partial(\rho i)}{\partial t} + \nabla\mathbf{.}(\rho i \mathbf{W}) = \frac{\partial p}{\partial t} - \frac{\partial(\rho \omega R V_\theta)}{\partial t} \\ - \nabla\mathbf{.}(\rho \omega R V_\theta \mathbf{W}) - \nabla\mathbf{.}(p\mathbf{U}) + \nabla\mathbf{.}(k\nabla T + \bar{\bar{\tau}} \cdot \mathbf{V}) + S_H.\end{aligned} \tag{6}$$

This equation has been derived starting from the well-known conservation of energy equation in MRF for absolute velocity formulation [7]:

$$\frac{\partial(\rho e)}{\partial t} + \nabla\mathbf{.}(\rho e \mathbf{W}) = -\nabla\mathbf{.}(p\mathbf{V}) + \nabla\mathbf{.}(k\nabla T + \bar{\bar{\tau}} \cdot \mathbf{V}) + S_H. \tag{7}$$

And substituting the energy expression

$$e = h_0 - \frac{p}{\rho} = i + \omega R V_\theta - \frac{p}{\rho} \tag{8}$$

leads to

$$\begin{aligned}\frac{\partial(\rho i)}{\partial t} + \frac{\partial(\rho \omega R V_\theta)}{\partial t} - \frac{\partial p}{\partial t} + \nabla\mathbf{.}(\rho i \mathbf{W}) + \nabla\mathbf{.}(\rho \omega R V_\theta \mathbf{W}) - \nabla\mathbf{.}(p\mathbf{W}) = \\ - \nabla\mathbf{.}(p\mathbf{V}) + \nabla\mathbf{.}(k\nabla T + \bar{\bar{\tau}} \cdot \mathbf{V}) + S_H.\end{aligned} \tag{9}$$

Reorganizing the final terms, Eq. 6 is obtained.

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