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## Overview of the IDEFFIX project: towards the development of the far-field exergy balance method at an industrial level of complexity

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### ABSTRACT

This paper presents an overview of recent research activities aiming firstly at extending the exergy balance method for aerodynamic performance analysis to highly-complex flows, and secondly at evaluating the interest of the method within an industrial design cycle. These activities were carried out in the frame of the IDEFFIX research project, in a collaboration between ONERA, Airbus and Safran Aircraft Engines. Their main objective is the investigation of this methodology (as well as exergy as an appropriate performance metric) beyond academic cases, using the implementation of the formulation within the FFX analysis software developed at ONERA. The activities of the project led to significant advances in terms of development of the underlying formulation and software functionalities for complex cases. In addition, several applicative tasks were undertaken both in a research context by ONERA and in an industrial environment by Airbus and Safran Aircraft Engines in order to assess the methodology in test cases representative of an industrial level of complexity.

### 1. INTRODUCTION

In a context of pursuit of improved aerodynamic performance for the sake of a reduced environmental impact of the aviation sector and the expansion of the flight envelope, the role of performance analysis is still of key significance for the research and industrial sectors. On this path, analyzing the influence of different physical phenomena on the aerodynamic characteristics of aircraft

or engine configurations is an essential aspect of applied aerodynamics research. For the industrial sector in particular, such an analysis can yield a refined understanding of flow features and a quantification of their influence on overall performance. This can in turn pave the way for design improvements and even orient design optimization.

For a wide range of aeronautics configurations, the evaluation of aerodynamic performance is based on force integrals on boundary condition surfaces (referred to as the near-field approach). For civil aircraft in particular, a driving metric of performance is the aerodynamic drag on the aircraft skin. Near-field methods for drag evaluation are traditionally limited to a mechanical breakdown of drag into a pressure and a friction component (although some recent works are aiming at refining this type of decomposition [1]). This breakdown is often insufficient in practice, for example due to the intertwining of multiple drag sources into pressure drag itself or due to the fact that viscous effects are not limited to the friction component. A phenomenological breakdown of drag into physical components can be performed by far-field drag analysis methods, which have been the focus of research at ONERA for several years [2, 3, 4]. These methods are nowadays mature and sufficiently accurate to be used in cases of realistic complexity.

More recently, the search for improved aerodynamic performance has led to the emergence of different innovations in aircraft architecture, e.g. ultra-high bypass ratio (UHBR) engines, boundary-layer ingestion (BLI), high-aspect-ratio (sometimes strut-braced) wing, blended wing-body or distributed electric propulsion, among others. Several of these architectures involve significantly-increased interactions between the airframe

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and the propulsion system, or even a strong influence of thermal effects on performance. The management of thermal aspects is particularly important to ensure consistent performance. This is even more so the case with the emergence of higher requirements for heat dissipation due to the reduced availability of a cold source (e.g. fuel) and the increased use of high-power electrical systems, and electric propulsion in particular.

While most configurations are not *fundamentally* different from current-generation aircraft, most of these cases involve particular intricacies which can notably affect their design orientations. A notable example is that of BLI concepts. Although these can be studied using momentum-based methods, such analyses may be found to be inappropriate. The highly-integrated engines of BLI aircraft make the task of drag/thrust bookkeeping rather ambiguous (see for example the discussion in [5]). In practice this is not only a methodology shortcoming but one of the design process itself. More specifically, this is because the performance gains expected by BLI are achieved by a strong synergy between the airframe and the engine. The separate analysis of the two components can therefore become less representative in itself compared to their integrated analysis.

This has led to the development of different approaches for performance evaluation. These were pioneered by the power balance method [6], which instead of momentum formulates a balance of mechanical energy to analyse the aforementioned ingestion effects due to engine integration in BLI cases [7, 8]. This was followed by the development of a balance method based on the concept of exergy [9, 10], which was implemented in a prototype analysis software and studied in a wide range of classical academic aerodynamics applications (cf. [9] and references therein). Although exergy is a commonly-used metric in classical thermodynamics [11, 12], its use is rather recent for the analysis of aerodynamics flows. In parallel to the activities presented in this paper, this method was also investigated by other authors, in particular with the aim of applying it to turbine cases [13] or extending it to the analysis of wind-tunnel data [14] and unsteady flows [15]. Others have considered the integration of exergy-based metrics alongside power-balance-based ones for BLI fuselage studies [16, 17].

In addition to mechanical energy, the exergy balance includes the influence of compressible and thermal effects, making it interesting for both classical and innovative configurations. This method is thus also particularly interesting beyond classical external aerodynamics, for example in the performance analysis of turbomachinery flows where the understanding of loss mechanisms is of primary importance [18]. Furthermore, it allows a detailed physical decomposition capable of quantifying the influence of individual reversible and irreversible physical phenomena on overall performance. Due to the

mentioned advantages of the exergy balance formulation, the IDEFFIX research project was structured in order to carry out the development and validation activities required to extend its application to highly-complex configurations.

The following part of the paper is structured as follows. First, Sec. 2 presents the structure and general objectives of the IDEFFIX project. Sec. 3 then gives an overview of the exergy balance formulation implemented in the FFX software of ONERA and Sec. 4 presents an overview of some of the project's activities before overall conclusions and perspectives of this work are discussed in Sec. 5.

## 2. STRUCTURE AND OBJECTIVES OF THE IDEFFIX RESEARCH PROJECT

The IDEFFIX (Industrial Development of Far-Field Exergy) research project was carried out in 2020-2023 with the support of the French Directorate for Civil Aviation (DGAC) and the European Union (EU) as part of the French national *Plan de relance* and the NextGeneration EU framework. The consortium was composed of ONERA, which was also the project coordinator, Airbus and Safran Aircraft Engines.

The main high-level objective of the project was to enhance the analysis and the functionalities of the FFX analysis software of ONERA, in the perspective of its use for flowfield analysis and aerodynamic design in the research and industrial sectors. At the same time, the activities carried out by the project's industrial partners aim at investigating the particular interest of the exergy balance method for the analysis of classical and innovative concepts. In this context, the project also aims at facilitating the dialogue between airframe and propulsion system manufacturers using common exergy-based performance and design metrics. The above are addressed through the following sub-objectives:

- Extension of the domain of validity of the formulation (e.g. internal flows and supersonic flow regime).
- Improvement of the physical interpretation of exergy-based metrics by studying their links with classical figures of merit, in particular for turbomachinery applications.
- Quantification and reduction of the influence of numerical errors in the analysis.
- Improvement of the FFX software's computational and analysis capabilities (e.g. complex boundary conditions, handling of very large grids).
- Validation of the analysis for cases of an industrial interest in terms of physics and geometrical complexity (aircraft, engine and heat exchanger flows).

The project activities are organized in three work packages. The first involves theoretical and numerical evolu-

tions of the exergy balance methodology, the second involves activities regarding the validation of these developments and the assessment of the method in benchmark cases, whereas the third one involves the application of the method to research configurations of the industrial sector. The first two work packages were carried out by ONERA, while the third was carried out by Airbus and Safran Aircraft Engines with the support of ONERA.

Finally, it should be noted that the activities of the ID-EFFIX project are in a strong synergy with those of the SUBLIME research project of ONERA, oriented towards BLI physics and also funded by the French DGAC. A mid-project synthesis of some of its research activities is presented in [19].

### 3. EXERGY BALANCE FORMULATION

#### 3.1 Exergy definition

The thermodynamic notion of exergy represents the maximum amount of work that can be extracted from a system through its interaction with a reservoir, here corresponding to its thermodynamic dead state, through reversible processes. Considering that the fluid is a perfect gas and by neglecting the gravitation potential energy, exergy is expressed as [11, 12]:

$$\chi = \delta e + p_\infty \delta \left( \frac{1}{\rho} \right) - T_\infty \delta s + \frac{1}{2} (\mathbf{V} - \mathbf{V}_\infty)^2 \quad (1)$$

where  $\rho$  is static density,  $e$  is specific internal energy,  $T$  is static temperature,  $p$  is static pressure and  $s$  is specific entropy. In addition,  $\delta(\bullet) = (\bullet) - (\bullet)_\infty$  is the perturbation of a quantity with respect to the reference state (denoted by the subscript  $\infty$ ). Note that Eq. (1) corresponds to a corrected adaptation of the exergy definition for aerodynamic flows [20], in particular considering a dead state that is not at rest but in motion at a velocity  $\mathbf{V}_\infty \neq \mathbf{0}$ .

#### 3.2 Exergy balance

A balance of exergy can be formulated in a control volume of fluid around an aircraft, or within a channel in the case of internal flow. In particular for the case of external flows, the boundaries of the control volume may extend far upstream and in the lateral directions. Its downstream limit is usually a transverse plane whose position is user-prescribed. This position may be varied in the course of the study in order to investigate the evolution of the exergy balance as the control volume is extended (and thus contains different physical phenomena). The variation can then be used as a measure of exchanges between terms of the balance (e.g. increased dissipation due to the inclusion of more regions of irreversible losses). In the

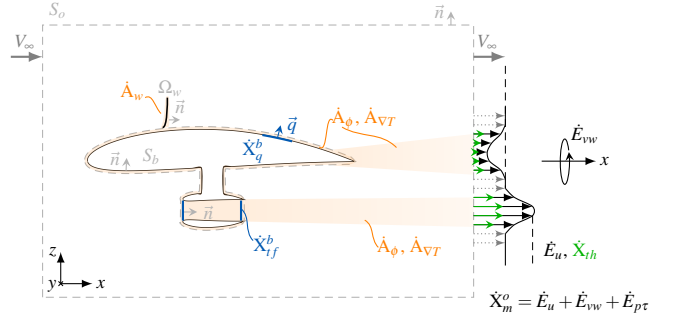


Figure 1: Schematic illustration of the exergy balance for a generic aircraft configuration, considering a dead state in motion at a velocity opposite to that of the aircraft.

case of a rotating computational domain, the control volume follows the rotation of the fluid volume and thus appears fixed in the corresponding rotating reference frame. Finally, the control volume may include shockwave discontinuities.

The system is thermodynamically open, as it exchanges mass, work and heat with its surroundings, across its boundaries. Note that, for the sake of brevity, the discussion of the balance in this paper will be limited to its compact form.

The exergy balance can be expressed in different forms, in order for the analysis to be better-adapted to the case under study [21]. A commonly-employed compact form of the balance is:

$$\dot{X}_r + \dot{X}_{tf} + \dot{X}_q = \dot{X}_{tr} + \dot{X}_m + \dot{X}_{th} + \dot{A}_\phi + \dot{A}_{VT} + \dot{A}_w \quad (2)$$

At the left-hand side of the above balance, the first term  $\dot{X}_r$  is the inflow of mechanical exergy into the fluid through rotating surfaces (i.e. equal to the shaft power in the case of a rotor). Then,  $\dot{X}_{tf}$  is the inflow of exergy into the fluid due to throughflow models. These are typically models of propulsion systems, heat exchangers or other elements adding exergy to the fluid (e.g. via boundary conditions or source terms).  $\dot{X}_q$  is finally the inflow of exergy into the fluid via conduction through non-adiabatic portions of the control volume's exterior surface (walls or fluid volume). Note that these terms are negative in the case of an outflow (or extraction) of exergy from the fluid. At the right-hand side,  $\dot{X}_{tr}$  represents the part of the provided exergy flux that is converted to effective thrust (overall axial streamwise force) for a configuration that is in translation with respect to the geocentric reference frame at a velocity  $-\mathbf{V}_\infty$  (cf. [20] for a more detailed discussion). The terms  $\dot{X}_m$  and  $\dot{X}_{th}$  represent a breakdown of the overall exergy flux through the control volume's outer surface. This breakdown is respectively into a mechanical (i.e. dynamic, null for  $\mathbf{V} = \mathbf{V}_\infty$ ) and a thermo-compressible (i.e. static) exergy flux, based on the defi-

dition of exergy in Eq. (1). The mechanical exergy flux  $\dot{X}_m$  can be decomposed into an axial kinetic perturbation energy outflow  $\dot{E}_u$  (jets, wakes, ...), a transversal kinetic perturbation energy outflow  $\dot{E}_{vw}$  (swirl, vortices, ...) and a contribution of the rate of work of surface forces  $\dot{E}_{p\tau}$  related to these kinetic energy perturbations. The final three terms represent the exergy dissipation, or equivalently anergy generation, due to irreversible effects.  $\dot{A}_\phi$ ,  $\dot{A}_{\nabla T}$  and  $\dot{A}_w$  are respectively the anergy generation due to viscous effects, thermal mixing and shockwaves, and are sometimes collectively referred to as the overall anergy generation ( $\dot{A}_{tot}$ ). A schematic illustration of the above terms is shown in Fig. 1. The complete version of the above balance can be found in [21]. In particular, Eq. (2) does not include the unsteady contributions to the different exergy flux terms, due to the analyses of this paper being limited to steady-state solutions. In the case of rotating-frame solutions all terms are projected in the relative frame of reference. For a null entrainment velocity the formulation is however simplified to its inertial-frame expression, which is important as it allows the uniform treatment of fixed and rotating components.

For an aircraft configuration, the balance of Eq. (2) expresses that the overall inflow of exergy into the fluid by rotating elements ( $\dot{X}_r$ ), propulsion system or heat exchanger models ( $\dot{X}_{rf}$ ) and non-adiabatic surfaces ( $\dot{X}_q$ ) is not completely converted into effective thrust ( $\dot{X}_{tr}$ ). The reason for this is the fact that part of this inflow leaves the control volume in the form of (theoretically) recoverable mechanical ( $\dot{X}_m$ ) or thermocompressible ( $\dot{X}_{th}$ ) exergy, whereas another is dissipated due to irreversible effects ( $\dot{A}_\phi$ ,  $\dot{A}_{\nabla T}$ ,  $\dot{A}_w$ ). Unless recovered by a mechanical or heat device, the recoverable exergy outflows  $\dot{X}_m$  and  $\dot{X}_{th}$  will also be dissipated by irreversible effects downstream. A way to view the exergy balance is thus as a decomposition of the part of exergy inflow that is not converted into effective thrust. This formulation can therefore quantify the impact of each of the above individual phenomena on the overall performance of the configuration.

Additional studies have been carried out to make the above breakdown better-adapted to specific cases. For example, in internal flow cases where the configuration's translation velocity is not known, it may be more appropriate to investigate the sum of the terms  $\dot{X}_{tr} + \dot{X}_m$  rather than their individual contributions [20, 21]. Another case is the decomposition of the overall exergy outflow  $\dot{X}_m + \dot{X}_{th}$  through the control volume boundaries, which is straightforward but may be found to be impractical. This is because reversible exchanges may take place between  $\dot{X}_m$  and the compressibility contributions to  $\dot{X}_{th}$ . A particular approach to improve this breakdown is by fixing a specific ideal path for the recovery of exergy, based on an isentropic expansion and an isobaric heat exchange [21, 22]. This allows the decomposition of  $\dot{X}_{th}$  as

$\dot{X}_{thse} + \dot{X}_{th\delta s}$ , respectively into a compressible and a thermal contribution. This in turn allows to express an overall exergy flux that is mechanically recoverable (e.g. by a turbine) as  $\dot{X}_{mr} = \dot{X}_m + \dot{X}_{thse}$ , and a thermally-recoverable one  $\dot{X}_{th\delta s}$  which is only recoverable by a heat engine (a Carnot machine in the ideal case). Finally, other works have been dedicated to analyzing the sensitivity of the above balance to numerical error [23, 24].

It is important to note that specific exergy-balance-based figures of merit can be constructed in order to accurately analyze the performance of the system under study. Due to the detailed breakdown of the above balance, it is rather straightforward to adapt these metrics to the needs of specific cases (e.g. by accounting for a recoverable exergy flux as a loss in a case where no device is present to recover it). A discussion of such aspects is given in [9], as well as in [21] with a further emphasis on turbomachinery cases.

### 3.3 FFX analysis software

*FFX* (Far-Field eXergy) is an exergy-based analysis software, developed at the Department of Aerodynamics, Aeroelasticity, Acoustics of ONERA. It is used for the post-processing of CFD results, with the goal of assessing the performance of configurations of various types and complexity levels using an exergy balance formulation. The software architecture of *FFX* is modular with a user interface in Python, which offers a high level of flexibility (scripting, coupling with other modules, etc). Internal computations are implemented in C++ for a combination of flexibility and computational performance. In particular, *FFX* can be used for the post-processing of data structured in the form of a CGNS/Python tree [25]. Its implementation is closely coupled with Cassiopée, a library of pre-/post-processing functions developed at ONERA [26].

The *FFX* module can accurately analyze finite-volume CFD solutions on structured, unstructured or overset (Chimera) grids. The solution can be computed at cell centers or at vertices. It can also take into account different methods used in the research or industrial field for the modeling of propulsion systems, heat exchangers or other devices (e.g. source-term modeling, actuator disk interfaces, particular boundary conditions). Some further developments carried out in the frame of the IDEFFIX project will be discussed in the following section.

The validation of *FFX* has been continuously pursued since the development of its prototype version, in the frame of both internal research activities at ONERA and external research/industrial collaborations. Such cases involve classical external aerodynamics cases [9, 27], studies specific to the analysis of numerical effects [23, 28, 24], the analysis of research configurations [29, 30, 31, 32, 33] and finally the analysis of research configurations of industrial interest [34, 35, 36, 37, 38, 39]. Several

validation activities were recently carried out in the frame of the IDEFFIX project.

## 4. OVERVIEW OF SOME RESULTS OF THE IDEFFIX PROJECT

This section aims at presenting a synthesis of some of the results obtained by ONERA, Airbus and Safran Aircraft Engines during the IDEFFIX project, by the use of *FFX* on several test cases. The list of presented results is not exhaustive, but remains representative of the main activities undertaken throughout the project. The studies presented in Secs. 4.1-4.3 were carried out by ONERA, whereas the studies presented in Sec. 4.4 were carried out by Airbus and Safran Aircraft Engines with the support of ONERA.

### 4.1 Methodology development

#### 4.1.1 Numerical accuracy indicators

Numerical errors may sometimes be acceptable in early design stages but must be limited as much as possible in fine performance analysis. Sources of numerical errors are however diverse in practice and thus their influence is often not well-analyzed, or even overlooked, on methods such as the exergy balance which aim at analyzing the flowfield details. The main objective of the present task was the quantification of the influence of numerical errors in the results of the analysis using the exergy balance method (cf. Fig. 2). The motivation behind this goal partly originated from previous activities aiming at isolating this error by the definition of a spurious anergy term and at studying the influence of the balance to numerical errors related to insufficient grid density or iterative convergence [23, 28]. The present work was a continuation of these studies by the development of a more fundamental and general approach for the quantification of this error. More specifically, this was carried out by the formulation of appropriate metrics (referred to as numerical accuracy indicators) allowing to measure the accuracy of the balance at the discrete level in a simple, reliable and robust manner. These measures were derived from the flow equations and allow to decompose the overall numerical error and give a more accurate evaluation of its impact on the overall balance. A notable aspect of this study is the fact that different terms of the balance can be affected by numerical error through different mechanisms. While the overall error of the balance is affected by parameters such as grid density and iterative convergence, a specific part of it is more directly associated with the resolution of irreversible losses. With grid refinement, this portion is reduced by both an improved resolution of these losses (shockwaves, velocity/temperature gradients) and a reduction of the excessive entropy generation

by numerical dissipation (cf. Fig. 3). Results indicate that the portion of the error related to the total energy balance can be effectively reduced using accurate standard CFD practice, whereas the rest (associated to anergy) relies on an accurate resolution of regions of irreversible loss, which is not always common practice in external aerodynamics applications. The insight given by the breakdown of the overall discrete error is thus of importance for the accurate assessment of numerical solution accuracy. Furthermore, such indicators can prevent designers from drawing conclusions based on CFD solutions which may be marked by significant numerical errors, and even aid in establishing more accurate numerical practices for aeronautics applications. More details on these developments and their application can be found in [24]. Finally, the developed methodology was used to evaluate the influence of numerical errors in all of the validation tasks of the project, as well as in other parallel research activities [29, 21, 31].

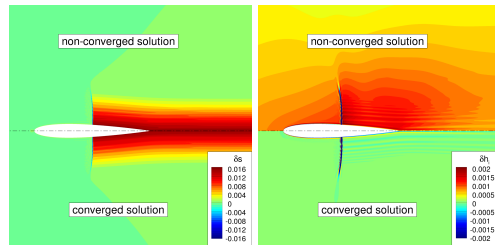


Figure 2: Influence of inadequate solution convergence on the flow details of an inviscid transonic flow around a NACA0012 airfoil, entropy (left) and stagnation enthalpy perturbation (right) [24].

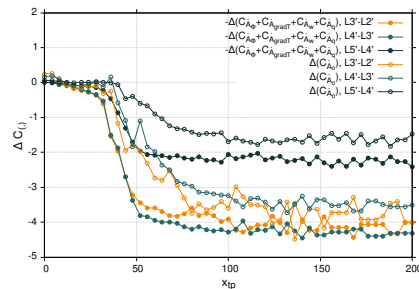


Figure 3: Influence of grid refinement on the discrete anergy balance components (NASA CRM) [24].

#### 4.1.2 Adaptation for the analysis of internal flows

The exergy balance derived in [20, 21] was derived under the only assumption that the system investigated can be considered as a perfect gas. The domain of validity of the obtained exergy balance is thus not limited to external flows, and as such it can be directly applied to cases of internal ones. Nonetheless, the derivation of this formulation has given a precious insight into some effects

which are essential to internal flows. On the one hand, these studies have demonstrated that the reference thermodynamic quantities are characteristic of the system's dead state for the exergy definition, whereas the reference velocity is actually representative of the reference frame transformation from the geocentric to one attached to the aircraft in motion (cf. [20, 21] for a further discussion). Moreover, the same work has given a more straightforward understanding of the influence of specific terms, in particular for unsteady flows or for flows where unbalanced mass flow enters or exits through the near-field boundary, steps which are important for the interpretation of results in complex flows, and especially internal ones.

Works parallel to the IDEFFIX project consisted in the application of this formulation to the NASA rotor 37 compressor configuration [30, 21], using an exergy balance projected in the rotating reference frame attached to the rotor. As discussed in Secs. 1 and 3, the exergy balance is particularly interesting in turbomachinery cases because it provides a detailed breakdown of different effects influencing overall performance, including mechanical, compressible and thermal effects. The exergy-based analysis of internal flows allowed to refine the performance investigation with respect to classical analysis, by providing clear phenomenological links between reversible/irreversible losses and physical phenomena occurring in the flow (not available in loss analyses based on overall entropy generation). In a synergy between the SUBLIME and IDEFFIX projects, links were also established between exergy-based and classical figures of merit (e.g. the isentropic efficiency), highlighting a richer physical content in exergy-related metrics of performance (e.g. the inclusion of the frictional reheat effect). The results obtained finally highlighted the need for a clear decomposition between thermal and compressible effects contained in the exergy balance, which led to the development and application of a decomposition between mechanically- and thermally-recoverable exergy outflows for the rotor 37 analysis [22, 21].

#### 4.1.3 Investigation of the method in supersonic flow regions

The objective of the present task was the investigation of the validity of the exergy balance in supersonic flow regime, aimed at evaluating the capacity of the method to treat highly-compressible turbomachinery cases (e.g. high-pressure compressor/turbine or even fan flows). The particularity of turbomachinery stages operating in transonic or supersonic regime is that shockwaves are not always contained within the control volume used for the analysis, but may extend upstream or downstream. The validation was carried out in two-dimensional external flows, where the influence of shockwaves extending far from the control volume can be studied in a more straightforward manner. At first, the study

was focused on the far-field drag breakdown, which is a reference method that can be sensitive to the aspect of shockwaves extending to the farfield boundary unless they are resolved by highly-accurate computational grids [3]. This has led to the improvement of the far-field drag breakdown method, in particular resulting in a methodology that is very robust with respect to the extent of the control volume boundary and in very good agreement with the theoretical wave drag values. Finally, the validity of the exergy balance method and the appropriateness of the current breakdown was investigated in the same inviscid and viscous flows. The exergy balance formulation was found to remain accurate in the case of shockwaves exiting the control volume. In particular, exchanges take place between different components of the balance close to the airfoil but a stable value in very good agreement with wave drag is obtained for the overall flux across the lateral surface (cf. Fig. 4). The results of the application to drag decomposition are shown in [40].

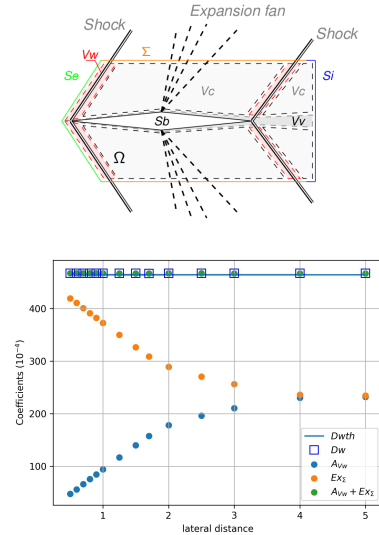


Figure 4: Illustration of sub-divisions of the control volume for the analysis of supersonic flows [40] (top). Sensitivity of the exergy balance with respect to the lateral distance of the integration surface from the airfoil skin (bottom).

#### 4.1.4 Software functionalities & evolutions

An important part of development activities was also focused on the *FFX* software itself, with the aim of improving its capacity in terms of treatment of complex solutions. This was first addressed by the development of a parallelization methodology prototype for such analyses in a distributed-memory MPI framework. Another part of the activity was aimed at the coupling of *FFX* with the CFD solver (e.g. analysis in memory coupling). For multi-stage turbomachinery cases in particular, devel-

opments were carried out for the accurate treatment of boundaries between rotor/stator rows (e.g, mixing plane or chorocronic boundaries). Finally, several implementations were aimed at improving the analysis and interpretation of results by the user, for example by appropriate treatments or data extractions.

## 4.2 Validation in academic cases

The initial part of validation activities was focused on academic configurations. The first and most fundamental case was the flow over the two-dimensional zero-pressure-gradient flat plate, which was studied in order to investigate grid convergence and the influence of boundary conditions in the results of the analysis. Several air-foil cases were then investigated in subsonic, transonic or supersonic regime for the validation of the developments presented in Sec. 4.1.

A further focus was then put on internal flows, in order to evaluate the recently-developed adaptations of the method in progressively complex cases (cf. Sec. 4.1.2). The first case was the Délerly bump, shown in Fig. 5, which is an empty wind tunnel with a deformed lower surface aiming at accelerating the flow until eventually generating a flow separation at the end of the bump. In addition, different flow regimes and shockwave structures can be obtained depending on the rear pressure of the outlet boundary condition. The ones analyzed were: a shock-free and separation-free case, a transonic case with a simple shockwave and finally a transonic case with a lambda shockwave interacting with the separation at the bump foot (also including a mild shock-induced separation in the upper wall surface). This case was very useful in terms of analyzing the different sources of irreversible loss, the conversion of exergy from one term to another along the channel, the analysis of the shockwave detection sensor, and finally the choice of reference state for the definition of exergy. Another validation case was the LMFA-NACA65 linear compressor cascade, which consists in an experimental test rig studying the impact of a turbulent boundary layer on fixed blades [41, 42]. Aside from the study of the exergy balance in internal flows itself, this test case was useful in terms of the analysis of losses and the study of turbulence model effects (cf. Fig. 6).

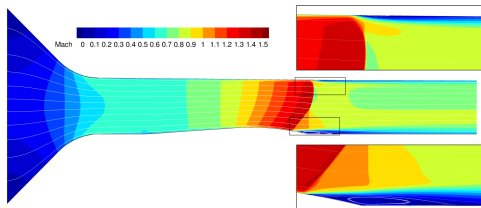


Figure 5: Visualisation of the lambda structure at the shockwave foot in the Délerly bump test case.

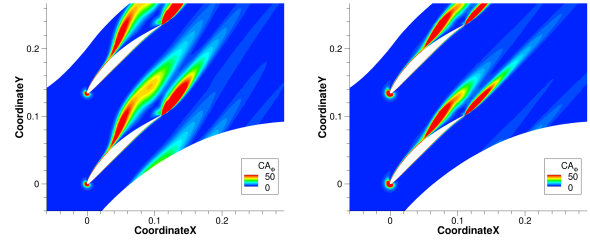


Figure 6: Exergy dissipation by viscous effects in the LMFA-NACA65 linear compressor cascade, obtained at a fixed height  $z=0.025\text{m}$  with different turbulence models: Spalart-Allmaras (left) and  $k-l$  with Quadratic Constitutive Relation (right).

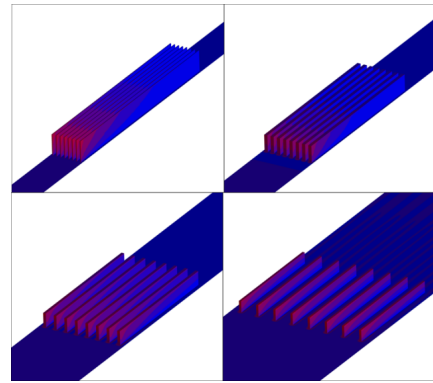


Figure 7: View of heat exchanger configurations with varying blade spacings [4].

In parallel, another academic application was aimed at investigating a flow involving both mechanical and thermal effects. The chosen case was that of a simple rectangular heat exchanger blade in an incoming freestream flow with a representative boundary layer. The study involved several configurations of different dimensions, and in particular different spacings for blades of the same dimensions considering the same total amount of dissipated heat (cf. Fig.7). The goal of the study was the analysis of heat dissipation compared against the added drag and the viscous or thermal losses due to the blades. Some results of this study are shown in [4]. It should finally be noted that this configuration is similar to that of a wind-tunnel experiment that will be carried out at ONERA in the frame of the SUBLIME project, and which will help in the further validation of the *FFX* module and of the underlying formulation.

## 4.3 Study of benchmark cases or concept configurations

As a following step to that of the analysis of academic flows, this section presents analyses carried out on benchmark test cases and concept configurations. The first



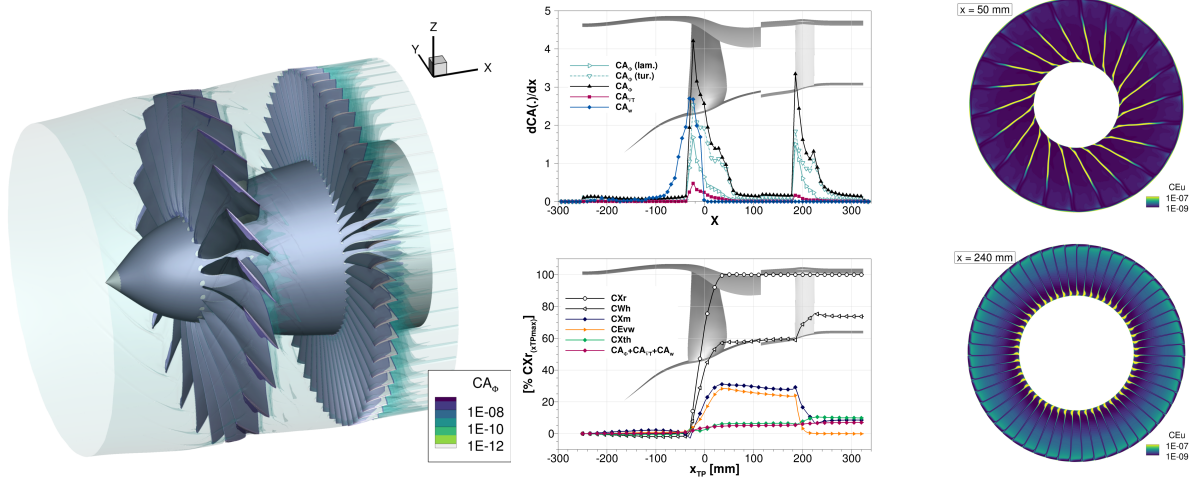


Figure 8: Isosurfaces of exergy dissipation, or energy generation, due to viscous effects (left), distribution of energy generation components along the axis and downstream evolution of exergy balance terms (middle), visualisation of streamwise kinetic exergy outflow (right) for a single-channel computation of the NASA SDT fan/OGV configuration.

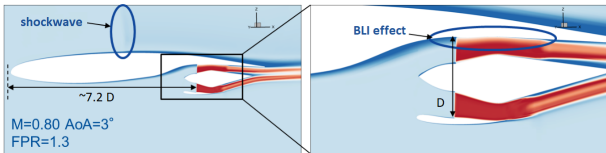


Figure 9: Visualization of the stagnation pressure field in a preliminary aerodynamic shape of the DRAGON concept configuration of ONERA.

is that of the NASA Common Research Model (CRM), which is a benchmark CFD and experimental case of recent AIAA Drag Prediction Workshops [43, 44]. This test case was first studied during the original development of the exergy balance formulation [27, 9]. The goal of the present task was the validation of developments discussed in Sec. 4.1, the investigation of computational performance, and the analysis of numerical effects (e.g. grid refinement and iterative convergence). The main results of this study are presented in [24]. In addition, part of this study was dedicated to the further validation of a methodology developed for the analysis of solutions on overset grids (developed in the SUBLIME project).

Next, two concept aircraft configurations of ONERA were studied as a demonstration of the use of the exergy balance throughout a design cycle. The first was a BLI-oriented configuration involved in an experimental campaign. The second was an intermediate shape of aerodynamic studies of the DRAGON configuration, shown in Fig. 9, which is a hybrid electric distributed propulsion concept of ONERA [45]. Although it is not its primary objective, this configuration involves a BLI effect which was analyzed and compared against preliminary estimates.

The final configuration of this category is the NASA Source Diagnostic Test fan rig, which is a benchmark fan / outlet guide vane (OGV) case designed to evaluate the noise-prediction capabilities of numerical methods against experimental acoustic data [46, 47]. In the scope of the present work, this is an important application of the exergy balance method for different reasons. Firstly, it is the first fan/OGV case of this type investigated with this method, as previous fan/OGV flows studied in the past were carried out on simulations where the blades were not resolved but modeled (actuator disks or source terms) [31]. This case thus represents a collective application and verification case for several newly-developed methodology or software developments required for its analysis. These are in particular the analysis of internal flows, of rotating blades in a rotating frame of reference and of turbomachinery-specific boundary conditions (mixing plane at the rotor and stator boundaries). Secondly, the test case was previously computed by ONERA in the frame of aeroacoustics studies, and thus includes a rich database of results in terms of numerical practices. The exergy-balance-based performance analysis has been carried out over multiple points of the characteristic curve, including some comparisons between baseline and higher-order space discretization numerical schemes, and isolated fan or fan/OGV computations. A particular point of interest was the identified influence of numerical scheme accuracy in the resolution of irreversible losses. The analysis has been found to be capable of accurately analyzing the fan module performance in terms of both mechanical/thermocompressible (theoretically recoverable) exergy fluxes and irreversible exergy losses. An illustration of results at one operating point is shown in Fig. 8. This shows the localisation of an-

ergy losses, the evolution of exergy fluxes along the axis (including the effective recovery of residual transversal perturbation kinetic energy by the OGV) and the analysis of visualisations of these local fluxes at specific axial positions.

## 4.4 Research configurations of industrial complexity

This section presents an overview of some cases investigated by the industrial partners of the IDEFFIX project, Airbus and Safran Aircraft Engines, in interaction with ONERA.

### 4.4.1 Aircraft configurations

The first group of activities revolved around external aerodynamics configurations of civil aircraft. In this framework, Airbus used *FFX* and the underlying exergy balance method for the analysis of an aircraft configuration with a classical engine integration. At a second step, the analysis was repeated for the Airbus NAUTILIUS boundary-layer-ingesting configuration. An older axi-symmetric design iteration of this configuration was also previously studied with *FFX* [37]. The purpose of the present task was a more representative study between the two types of aircraft architectures, involving detailed geometries in order to obtain a fairer comparison. The activity involved comparisons between the two configurations in terms of the exergy balance method, as well as a comparison of these results against far-field drag decomposition data. A notable aspect of these works was the study of criteria which allow to define a control volume yielding a representative comparison between very different aircraft architectures. In parallel, Safran Aircraft Engines used *FFX* in the analysis of a classical engine integration test case in order to identify the main mechanisms driving such a study in the exergy balance framework.

### 4.4.2 Engine component configurations

Safran Aircraft Engines carried out specific activities to assess the use of the exergy balance method in a study of individual engine components. The main type of components studied in this frame was exhaust nozzles, generally long-duct configurations with different exhaust mixers. This is a continuation of previous analyses using *FFX* on such configurations [34, 36]. A reference case was first investigated from a numerical point of view, aiming at evaluating the accuracy of the obtained exergy balance using an industrial simulation strategy, as well as at establishing robust standard practice for exergy-based analyses (e.g. grid refinement, convergence, numerical scheme parameters and boundary conditions). At a following

step, the analyses were focused on different exhaust mixers (unmixed flow and different mixer geometries up to a configuration of realistic complexity) and jet temperatures in order to quantify the influence of different physical mechanisms on the overall performance.

Another test case of this type was a fan/OGV configuration aimed at evaluating the integration of a Surface Air-Cooled Oil Cooler (SACOC) in the secondary stream of a turbofan engine, which is further discussed in Sec. 4.4.3.

### 4.4.3 Heat exchanger configurations

This section presents activities of both Airbus and Safran Aircraft Engines concerning heat exchanger configurations. These are interesting for both industrial partners as the need for efficient heat management is important in both the airframe and engine design. As discussed in the previous sections, the exergy balance is particularly interesting for the overall analysis of such flows as it considers mechanical, compressible and thermal effects in a single formulation. It is therefore particularly interesting for the analysis of eventual tradeoffs or synergies between efficient thermal management and aerodynamic losses due to the integration of the associated system.

The activities of Safran Aircraft Engines were oriented towards Surface Air-Cooled Oil Cooler (SACOC) configurations. The study started from simple-fin SACOC geometries, allowing an analysis of grid convergence and boundary conditions of increasing complexity on the fin surface: adiabatic, constant temperature and variable distribution computed by an aero-thermal coupling [48] (cf. Fig. 10). This comparison was interesting in order to establish accurate numerical practice for such flows and to evaluate the impact of higher-fidelity boundary conditions on the exergy balance results, in particular on the viscous and thermal exergy loss terms. The following step consisted in a slightly more complex configuration of a 16-fin SACOC in a wind-tunnel test section, shown in Fig. 11. The imposed incoming flow in this case contains the wake of an OGV, as a step towards more realistic operating conditions. The last case of heat-exchanger-related activities by Safran Aircraft Engines was a single-channel computation of a realistic configuration of a fan/OGV (joined by a mixing plane boundary condition), followed by a by-pass duct (BPD) including a SACOC in the wake of the OGV. A view of the configuration is shown in Fig. 11. As in the previous studies, the heat flux distribution on the SACOC blades was the result of a coupled aero-thermal simulation [48]. This test case, involving rotating/fixed components and mechanical/compressible/thermal effects, was interesting in terms of the analysis of the fan module in the exergy balance framework, as a continuation of the first application of *FFX* in a fan/OGV configuration (cf. Sec. 4.3). Moreover, it consists in the following step of the previ-

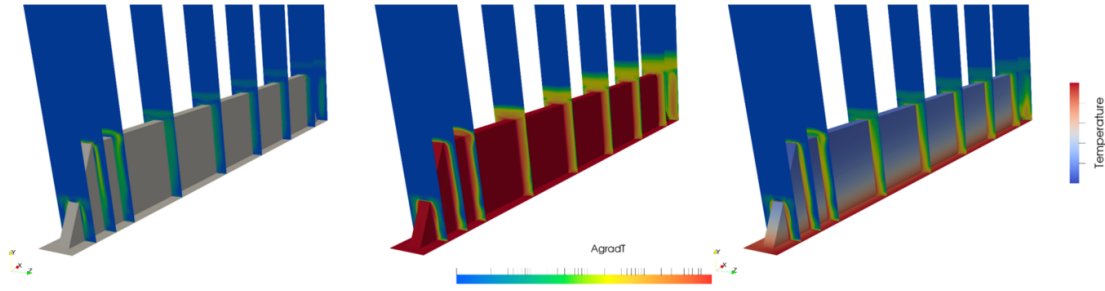


Figure 10: Field of thermal energy (thermal diffusion) for a SACOC fin using adiabatic (left), isothermal (middle) and aerothermal-coupling-based (right) boundary conditions [39].

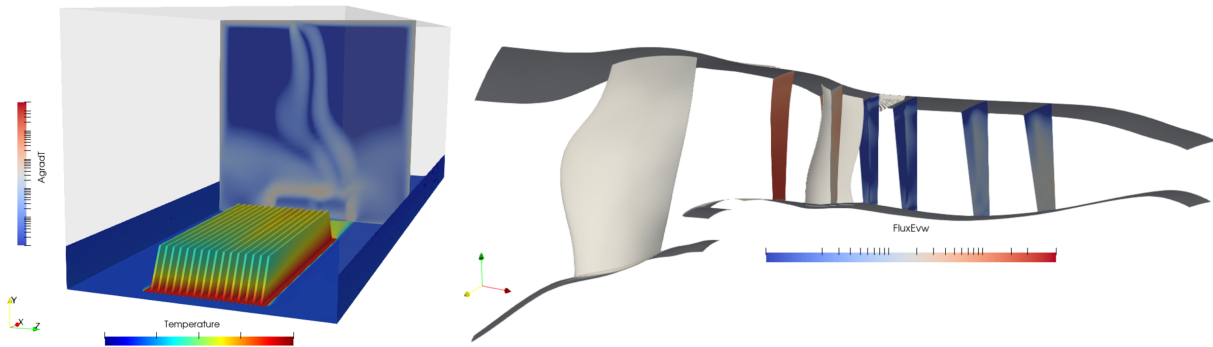


Figure 11: Field of thermal energy for the 16-fin SACOC configuration in a wind tunnel test section (left) and transversal kinetic energy outflow for a configuration including the fan/OGV/BPD and a SACOC (right) [39].

ous SACOC studies in terms of a representative example of integration of such a device in an aircraft engine. Some more detailed results of the analyses on SACOC configurations are presented in [39].

In parallel, Airbus worked on the analysis of a simplified channel flow including a heat exchanger whose effect into the flow is modeled by source terms (shown in Fig. 12). The goal of this study was to gain a preliminary but precise understanding of the effects of heat exchanger models on the terms of the exergy balance. For this purpose, the newly-developed decomposition of thermocompressible exergy into a compressible and a thermal term was also employed [22], confirming that almost all of the exergy flux injected to the fluid was only thermally-recoverable and giving a further physical insight on the system's exergy-based efficiency. Some more details on this study are given in [38].

#### 4.4.4 Propulsion system configurations

The present section presents an overview of some applications involving an innovative propulsion system. This is an open fan configuration related to the CFM RISE program (cf. Fig. 13), which enables much larger diameters and by-pass ratios than classical turbofans. Its rotor is responsible for the largest portion of thrust generation, with a stator row being placed downstream in order to

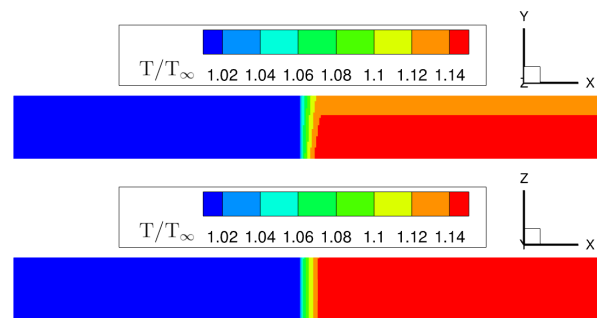


Figure 12: Temperature variation across the channel due to the heat exchanger model [38].

convert the swirl of the rotor into additional thrust. Such engines are promising candidates for powering the next generation of passenger aircraft. A model open fan configuration of this type was designed by Safran and studied by Safran, Airbus and ONERA in the frame of the INPRO research project. Exergy-based analyses of this test case were carried out in the IDEFFIX project by both Airbus and Safran Aircraft Engines. The goal of these studies was twofold. At first, it was to provide a refined understanding of the principal mechanisms affecting engine performance, in the view of ultimately assisting the evaluation of the interest of such engines with respect to

more conventional ones (e.g. UHBR turbofan). The second objective was to employ the exergy balance method and the *FFX* module in the validation of methodologies used in the design of similar engine types. An important aspect of this task is the validation of methodologies by airframe and engine manufacturers using a common performance analysis tool.

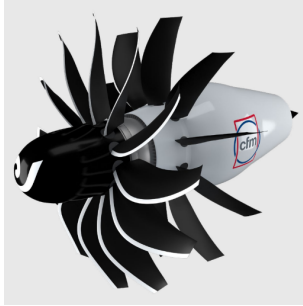


Figure 13: Illustration of the open fan concept of the CFM RISE program (image property of CFM International, reproduced with permission).

Airbus studies focused mainly on CFD methodology validation and physical analyses (e.g. nacelle effects). Regarding the former aspect, comparisons were carried out between different modelling approaches for the rotor and stator blades. The simplified models used in RANS computations were a virtual blade method and a body-force method, both of which model the effect of the rotor and stator rows through source terms. Results of the exergy balance using these methods were compared against a reference single-channel computation resolving the rotor and stator blades (respectively in a rotating/fixed reference frame, the two being connected by a mixing plane boundary). The analyses showed a good agreement of the aforementioned three approaches in terms of the overall balance and established clear links between the evolution of the exergy balance and the flow physics (e.g. compressible effects or the swirl recovery by the stator). Finally, this analysis also highlighted specific finer differences between the models, in particular regarding their accuracy in the representation of the flow (e.g. blade-tip vortices, cf. Fig. 14) and that of exergy dissipation/loss due to irreversible effects. Some further details on these studies are given in [38].

Safran Aircraft Engines focused on using the exergy balance method to analyze cases of a generally higher level of geometrical and physical representation. The first case was also a single-channel mixing plane computation at cruise conditions. Further details were then included by the consideration of a  $360^\circ$  geometry modeling the rotor by a virtual blade model and resolving the stator blades. Comparisons were carried out between more realistic geometries including a pylon and nozzle, as well as between cruise and takeoff conditions. These allowed to

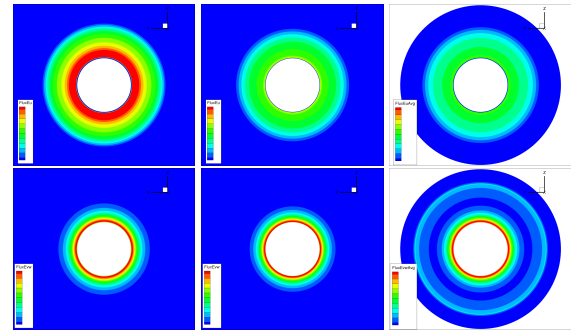


Figure 14: Visualisation of the streamwise (top) and transversal (bottom) perturbation kinetic energy fluxes at a transverse plane downstream of the stator for three different modeling approaches. VBM (left), BFM (middle) and azimuthally-averaged result of a single-channel computation resolving the blade geometry (right) [38].

clearly link the results of these comparisons to the flow-field details, and thus to quantify the influence of each individual phenomenon on the overall engine performance for the corresponding geometry and operating point.

## 5. CONCLUSIVE REMARKS

The IDEFFIX research project has consisted in an important step towards the wider use of the exergy balance method in the analysis of both research and industrial configurations. Works in terms of the development of the formulation were undertaken by ONERA, in order to ensure the accurate treatment of complex flows involving mechanical, compressible and thermal effects. Validations of multiple levels of complexity were carried out by ONERA, Airbus and Safran Aircraft Engines to assess the accuracy and consistency of the analysis. These studies confirmed the potential of the method for the performance evaluation of complex configurations, by providing a refined physical insight and a quantification of the influence of individual flow mechanisms (and their interactions) on this performance. Overall, the capacity of the *FFX* software and of the underlying exergy balance method regarding the treatment of physically- and geometrically-complex configurations was significantly expanded through the activities of the IDEFFIX project.

For the research sector, such approaches can provide a precious insight in terms of flowfield analysis. In an industrial context, these works aspire to allow designers to achieve more efficient designs by understanding and quantifying the influence of specific physical phenomena on overall performance in order to be able to reach finer multi-disciplinary optima (e.g. aero-thermal system integration), as well as to facilitate the dialogue between airframe and engine manufacturers by the use of exergy as a common performance metric, especially regarding

engine integration on future aircraft. Future works will consider further extensions of the *FFX* module and of the underlying exergy balance formulation in order to extend the analysis to even more complex flow physics and realistic configurations representative of the future generations of aircraft.

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