THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING IN FLUID DYNAMICS

On Exergy and Aero Engine Applications

OSKAR THULIN

Department of Applied Mechanics
CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2016

On Exergy and Aero Engine Applications
OSKAR THULIN

Thesis for the degree of Licentiate of Engineering 2016:04
ISSN 1652-8565
Department of Applied Mechanics
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone: +46 (0)31-772 1000

Chalmers Reproservice
Gothenburg, Sweden 2016

On Exergy and Aero Engine Applications
Thesis for the degree of Licentiate of Engineering in Fluid Dynamics
OSKAR THULIN
Department of Applied Mechanics
Chalmers University of Technology

Abstract

Aero engine performance analysis is highly multidimensional using various measures of component performance such as turbomachinery and mechanical efficiencies, and pressure loss coefficients. Using conventional performance analysis, relying on only the first law of thermodynamics, it is possible to understand how the performance parameters affect the component performance, but not how the component performance relates to the system performance. A comprehensive framework has been detailed to analyze an aero engine in one common currency by complementing the analysis with the second law of thermodynamics. As it yields a measure of the lost work potential in every component it is used to relate the component performance to the system performance. The theory includes a more detailed layout of all the terms that apply to a propulsion unit than presented before and is here adopted to real gases to be used in state of the art performance codes. The theory is also extended upon by presenting the *installed rational efficiency*, a true measure of the propulsion subsystem performance, including the installation effects of the propulsion subsystem as it adds weight and drag that needs to be compensated for in the performance assessment.

The exergy methodology is applied to a modern direct-drive two-spool turbofan, chosen for its dominating market share in modern commercial aviation. The loss sources during an aircraft mission are then assessed and yield the major contributors in the entropy generated during combustion, the thermal energy leaving the nozzle and the exhaust nozzle kinetic energy that is not contributing to the thrust. Radical technology that can be utilized to address each specific loss are thereafter detailed. This includes intercooled and recuperated cycles, reheated cycles, bottoming Rankine cycles, pulse detonation combustion, piston topped composite cycles, nutating disc combustion, and open rotor and other ultra high bypass architectures.

Keywords: Aero engine, Exergy analysis, Performance modelling, Installed propulsion unit performance, Turbofan

"Genius is one percent inspiration, ninety-nine percent perspiration."

- Thomas A. Edison

Acknowledgements

I would, first and foremost, like to express my sincere appreciation to my main supervisor, Professor Tomas Grönstedt at Chalmers University of Technology, for all the support throughout this work. Thank you for making me wanting to strive further every day. I also owe my deepest gratitude to my co-supervisor Ph.D. Jean-Michel Rogero at Airbus S.A.S for his continued interest in my research project. Jean-Michel, I truly appreciate your curiosity for studying new ideas. Without Tomas's and Jean-Michel's extensive knowledge, passion for aviaton and for being such nice people to work with, I would not have developed this much nor would it have been this joyful. I also would like to recognize Ph.D. Anthony Roux and Ph.D. Alexandre Neophytou for their extensive help and positive collaboration.

A big *thank you* goes out to all the past and present colleagues at Chalmers. I consider it an honor to work with you and you make the time spent at Chalmers so much more worthwhile. I especially want to thank Sebastian Samuelsson, Xin Zhao, Martin Johansson, Lars Ellbrant and Hamid Abedi for the rewarding research talks and for being such good friends.

Finally, I would also like to express my gratitude to Airbus S.A.S. for funding this work.

Nomenclature

A	Area $[m^2]$
B	Arbitrary conserved extensive property
C	Velocity relative the reference frame of the earth's surface $[m/s]$
D	Drag $[N]$
F	Thrust $[N]$
HHV	Higher heating value $[J/kg]$
L	Lift $[N]$
L/D	Lift over drag coefficient $[-]$
LHV	Lower heating value $[J/kg]$
$\dot{\mathrm{I}}$	Irreversibility rate $[J/s]$
$\dot{\mathrm{I}}^\star$	Normalized irreversibility rate $[-]$
M	Molar mass $[kg/mol]$
P	Power $[J/s]$
$\dot{Q}$	Heat transfer rate $[J/s]$
R	Specific gas constant $[J/(kgK)]$
S	Entropy $[J/K]$
SFC	Specific fuel consumption $[mg/(Ns)]$
T	Temperature $[K]$, Thrust $[N]$
U	Flight velocity $[m/s]$
V	Velocity relative the reference frame of the aircraft $[m/s]$, Volume $[m^3]$
a	Acceleration $[m/s^2]$, Number of carbon atoms in a fuel molecule
b	Number of hydrogen atoms in a fuel molecule
c	Number of sulfur atoms in a fuel molecule
c_{p}	Specific heat capacity $[J/(kgK)]$
d	Number of oxygen atoms in a fuel molecule
e	Specific internal energy $[J/kg]$, Number of nitrogen atoms in a fuel molecule
$\vec{f}$	Force vector field $[N/kg]$ i.e. $[m/s^2]$
g	Gravitational constant $[m/s^2]$
h	Specific enthalpy $[J/kg]$
m	Mass $[kg]$
$\dot{m}$	Mass flow $[kg/s]$
$\hat{n}$	Unit normal vector $[-]$
p	Pressure $[N/m^2]$
s	Specific entropy $[J/(kgK)]$
t	Time $[s]$
$\vec{u}$	Vector velocity $[m/s]$
x	Mole fractions $[-]$
y	Mass fractions $[-]$

Δ	Difference
$\Delta_{\mathrm{f}}^{\circ}$	Thermodynamical property of formation at standard state conditions
$\dot{\Pi}$	Entropy production rate $[J/(sK)]$
Ψ	Rational efficiency $[-]$
α	Angle of attack $[^{\circ}]$
β	Mass fractions in fuel $[-]$, Arbitrary conserved intensive property
δ	Deviation angle between aircraft direction and engine direction $[^{\circ}]$
ε	Specific exergy $[J/kg]$
γ	Path angle $[^{\circ}]$
λ	Mass fraction of combustion products per unit burned fuel $[-]$
θ	Attitude $[^{\circ}]$
ρ	Density $[kg/m^3]$
$\vec{\tau}$	Shear stress vector $[N/m^2]$

Subscripts/Superscripts

D	Drag
L	Lift
S	Shaft
T	Thrust
W	Weight
i	Index of summation in components / mass constituents
in	Into control volume
j	Index of summation over components
n	Upper bound of summation
out	Out of control volume
pot.	Potential
prop. syst.	Aircraft propulsion system
prop. unit	Aircraft propulsion unit
rel.	Relative
ss	Standard state
syst.	System level
th.	Thermomechnical
∞	Ambient condition
0	Total properties

Thesis

This thesis consists of an extended summary and the following appended papers:

Paper A O. Thulin, J.M. Rogero and T. Grönstedt, 2015, "A Mission Assessment of Aero Engine Losses, *"International Society for Airbreathing Engines,"* ISABE-2015-20121, Arizona, USA

Paper B T. Grönstedt, M. Irannezhad, L. Xu, O. Thulin, A. Lundbladh, *"First and second law analysis of future aircraft engines,"* Journal of Engineering For Gas Turbines and Power, vol. 136, 2014.

Paper C X. Zhao, O. Thulin and T Grönstedt, *"First and second law analysis of intercooled turbofan engine,"* Journal of Engineering For Gas Turbines and Power, 2015.

Contents

Part I
Extended Summary

1 Introduction

Achieving more efficient aircraft and propulsion systems is of paramount importance in the aerospace industry. Propulsion system development, selection and integration poses a complex challenge as it constitutes a highly multidimensional and tightly coupled system. Performance studies based on the first law of thermodynamics will illustrate how the parameters, such as turbomachinery efficiencies, mechanical efficiencies and pressure loss coefficients, affect the component performance but will not give any information how the component behavior relates to the overall performance. The conventional way to assess potential improvements of propulsion units through parametric studies on a baseline model does not allow for a way to make the losses comprehensible, only to study the effect of an incremental change. The exergy methodology allows for analysis that asses the component contribution to the overall losses in an unified framework that also makes it possible to relate the different component losses to each other.

Using the exergy methodology allows analysis of the engine performance in one common currency, that fully takes advantage of the possibilities in the first and second law of thermodynamics. Exergy calculations relate the thermodynamical properties of a fluid stream to an equilibrium state to determine the work potential at each station in the engine. The further away the thermodynamical properties are from the equilibrium state, the larger the work potential is. Tracking the loss of work potential in each component throughout the cycle clearly indicates where the irreversibilities occur. This will lead to a more illustrative way of presenting the losses, and thus enabling better understanding how the component losses relate to the system performance. Moreover, the developed framework detailed in this thesis can be used to address the loss sources in an aero engine more systematically and to explore innovative propulsion unit architectures in search for lower fuel consumption and consequently less emissions.

Horlock and Clark pioneered the field of exergy analysis by applying it to a turbojet as early as 1975 [1]. Their original work was derived from extending the work of Evans [2]. In 1995, Brilliant extended the analysis for a turbofan engine [3] which was studied at the cruise point. Roth and Mavris published a series of papers assessing the performance of a Northrop F-5E “Tiger II” lightweight fighter plane, powered by two J85-GE-21 turbojets, including a full mission study from 2000 [4]. Rosen provided a mission analysis of a commercial turbofan in 2009. However the assumed engine performance and flight conditions were far from a typical airline operation which caused that the analysis failed to provide understanding of the loss sources.

Grönstedt et al. used exergy analysis in the cruise point to evaluate different future commercial engine concepts including a turbofan reference corresponding to a year 2050 technology level, an intercooled and recuperated engine, a pulse detonation combustion engine and an open rotor engine [5]. Zhao et al. continued the exploration of exergy analysis by applying it to better understand the benefits of intercooling in turbofan aero engines [6]. Thulin et al. published a mission study of a commercial turbofan in 2015 that provided analysis of the main mission points that constitutes a commercial mission [7]. The studied engine was more specifically of a direct-drive two-shaft type set up to represent a technology level corresponding to 2020. The engine architecture was chosen due to its dominating market share in modern aviation. The analysis did not only include the engine assessment in terms of the thermodynamic cycle but rather the full impact of the propulsion system including the weight and drag that inherently needs to be compensated for by engine.

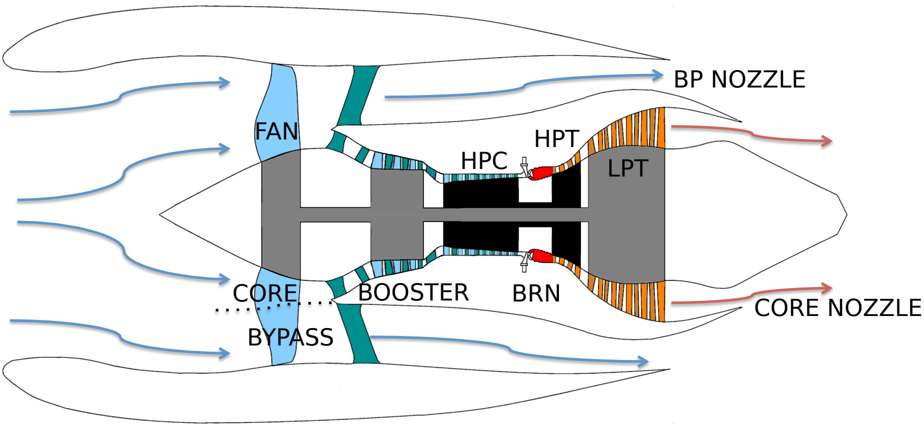

Figure 1.1: *Schematic of a direct-drive two-shaft type turbofan with the main components denoted.*

As illustrated in Fig.1.1 the engine takes in cold air and adds work to it in the ducted fan (FAN). The air is then divided into a bypass flow and a core flow. This is the fundamental difference between the turbofan and a turbojet, as the latter instead lets all mass flow go through a single passage that works similar to the turbofan core. The bypass flow continues via the bypass duct and out through the bypass nozzle where it is accelerated to create a propulsive force that propels the aircraft forward. The fan cannot run without any power supply, this is where the core flow comes in. The air that is directed through the core flow is then pressurized in two compressors. For a two-shaft turbofan, as illustrated in the picture, these are called booster and high pressure compressor (HPC). The fan and the booster are powered by the same shaft while the high pressure compressor is powered by a second shaft. Fuel is injected into the compressed air in the combustor (BRN) where the air and fuel mixture is also ignited. This increases the energy of the gas. Parts of the energy in the flow is extracted downstream in the two turbines, the high pressure turbine and the low pressure turbine, to power the compressors and fan on the respective shaft. The gas mix then exits the core nozzle to add to the propulsive force that propels the aircraft.

To give an indication of the value an exergy analysis can offer for the analysis of the engine irreversibilities a total system assessment is illustrated in Fig.1.2 and Fig.1.3. About thirty percent of the total work potential in the fuel is useful for the aircraft. Another four percent is lost due to the installation effects of the engine in terms of the added weight and drag that needs to be compensated for. About two thirds is lost as irreversibilities in the propulsion unit. These are dived into groups corresponding to the different sources in the engine irreversibility breakdown. The direct feedback of how the losses relate to the system performance is made very transparent by adding exergy analysis next to the conventional performance analysis.

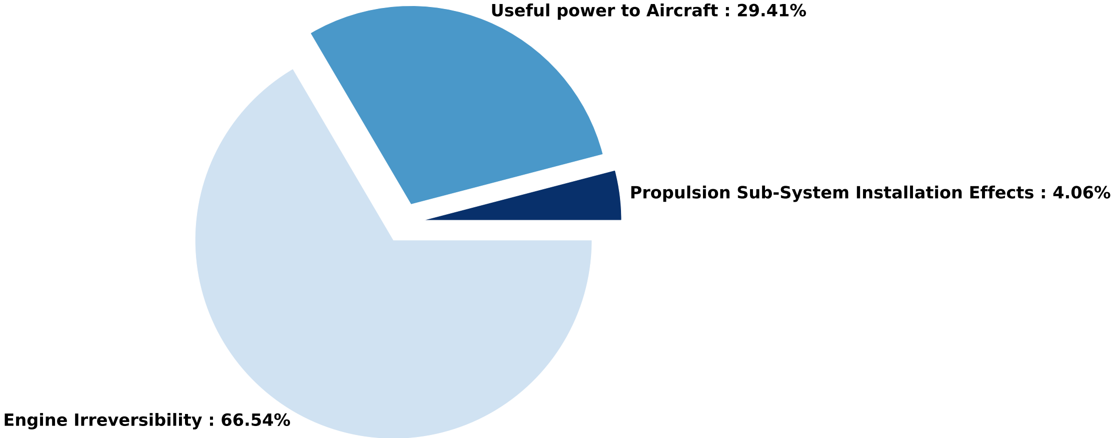

Figure 1.2: *A simplified short mission total exergy breakdown for a modern turbofan (Thulin et al. 2015 [7]).*

All studies above have been made possible through performance calculations. Exergy has also been applied in CFD analysis of combined aircraft and propulsion system simulations. Arntz and Merlen developed a theoretical framework for assessing aerospace applications through CFD studies [8]. This work targeted enabling precise analysis of a combined aircraft and propulsion system in a blended wing-body configurations with integrated propulsions units where the aerodynamics and the propulsion cannot be decoupled. The methodology was later on applied to the NASA Common Research Model [9], a geometric representation of a long-range wide-body twin-engine aircraft.

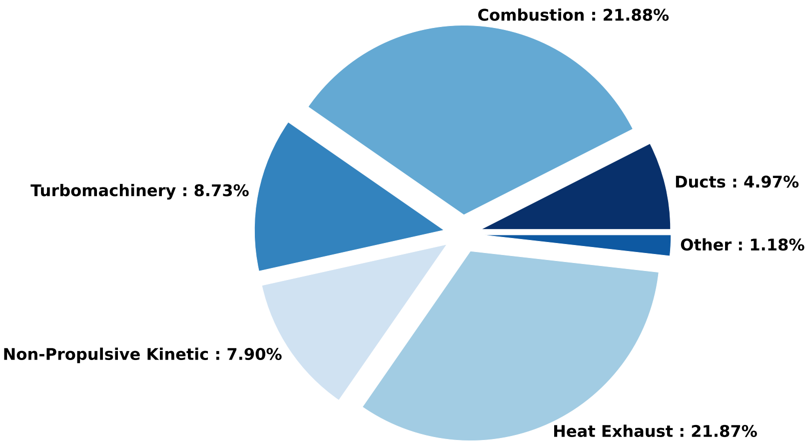

Figure 1.3: *A simplified short mission engine irreversibility breakdown of a modern turbofan (Thulin et al. 2015 [7]). When the irreversibility percentages are summed up they correspond to the engine irreversibilities divided by the provided fuel exergy as illustrated in Fig.1.3.*

1.1 Purpose

The purpose of this work has been to quantify the losses in aircraft propulsion units in a more systematic and illustrative way. By using the developed framework better understanding of the component losses can be enabled. Knowing how the component losses relates to the system performance can then be utilized in the search for more efficient engine configurations.

2 Exergy and Propulsion

This chapter details exergy applied to propulsion which is central in this thesis. The fundamental exergy equations are described and the terms used in the exergy equations are later derived and presented. Installation effects of the propulsion subsystem are assessed leading up on installed rational efficiency. Mission assessments are finally made building on the previous detailed exergy theory.

2.1 Exergy Applied to Propulsion

The most significant energy fluxes in an aero component are thrust, mechanical work, kinetic energy, thermomechanical energy, chemical energy and heat. These fluxes are therefore included in the aero engine exergy analysis presented here. The formulation is based on the work of Horlock and Clark [1]. They provided the analysis for the assumption of perfect gas. However, the treatment has here been adopted to real gases to be used in state of the art engine performance codes.

The maximum work that can be obtained for an aero engine system is given by Eq.2.1 and is illustrated in Fig.2.1.

$$\left(\sum_{\mathrm{i}} \dot{m}_i \varepsilon_i\right)_{\mathrm{in}} \geq \mathrm{P_S} + \mathrm{P_T} - \sum_i \int \frac{T - T_\infty}{T} d\dot{Q}_i + \left(\sum_i \dot{m}_i \varepsilon_i\right)_{\mathrm{out}} \tag{2.1}$$

where m_i = mass of constituent i in the mixture
ε_i = specific exergy of constituent i in the mixture, detailed in Eq.2.21 & Eq.2.30
$\mathrm{P_T}$ = thrust power extracted from the control volume, detailed in Eq.2.14-2.17
$\mathrm{P_S}$ = shaft power extracted from the control volume
$\dot{Q}_i$ = heat transfer rate into the control volume
T_i = temperature at heat transfer

The maximum work is obtained in the reversible limit at which equality holds [10]. The equation corresponds to the exergy balance of the incoming and outgoing exergy fluxes and is a measure of the irreversibility of the system.

The irreversibility rate, also called the exergy destruction, $\dot{\mathrm{I}}$, is formed as a difference when bookkeeping the exergy crossing the boundaries of a control volume:

$$\dot{\mathrm{I}} = \left(\sum_i \dot{m}_i \varepsilon_i\right)_{\mathrm{in}} - \left(\sum_i \dot{m}_i \varepsilon_i\right)_{\mathrm{out}} - \mathrm{P_S} - \mathrm{P_T} + \sum_i \int \frac{T - T_\infty}{T} d\dot{Q}_i. \tag{2.2}$$

Note that when the reference environment is set to the ambient conditions, the total magnitude of exergy that enters into the system is equal to the exergy of the fuel. Relating

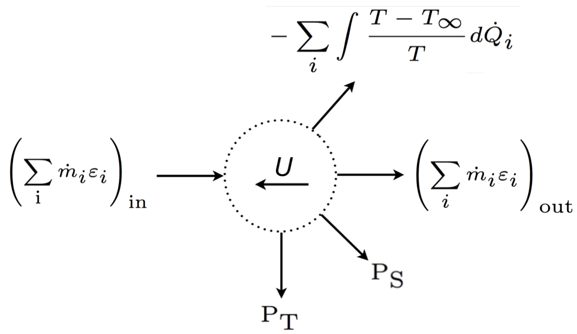

Figure 2.1: *Second law of thermodynamics applied to the reference frame of the engine*

the component irreversibilities to the total exergy gives the ratio of irreversibility for each component, then

$$\dot{\mathrm{I}}^\star = \frac{\dot{\mathrm{I}}}{\dot{m}_{\text{fuel}}\varepsilon_{\text{fuel}}}. \tag{2.3}$$

Adding up all the irreversibility contributions give a ratio of the total irreversibility

$$\dot{\mathrm{I}}^\star_{\text{syst.}} = \frac{\sum_j \dot{\mathrm{I}}_j}{\dot{m}_{\text{fuel}}\varepsilon_{\text{fuel}}}. \tag{2.4}$$

The rational efficiency expresses the useful work of a control volume in relation to the incoming exergy flux. The useful power generated by the aero engine is the thrust it provides to the aircraft as well as the bleed and power it potentially supplies to the cabin. Cabin bleed and power are not commonly included in the rational efficiency term. However, since they provide useful work for the aircraft they should be included in the useful work term and therefore we define

$$\Psi_{\text{syst.}} = \frac{\mathrm{P}_{\mathrm{T}\,\text{prop. unit}} + [(\dot{m}\varepsilon)_{\text{bleed}} + \mathrm{P_s}]_{\text{cabin}}}{\dot{m}_{\text{fuel}}\varepsilon_{\text{fuel}}}. \tag{2.5}$$

2.2 Exergy Fundamentals

Using the gas enthalpy it is possible to quantify the energy difference between the fluid stream at an arbitrary station in an engine to when the fluid stream is in equilibrium with its surroundings. Part of this energy will however be inaccessible even if the fluid stream would be taken to equilibrium in an ideal process. The equilibrium temperature multiplied with the entropy difference between the fluid stream and equilibrium state quantifies the energy that is inaccessible. Combining the total energy and the inaccessible energy yields the work potential of the fluid stream, or namely exergy, it reads

$$\text{Exergy} = \text{Work potential} = \text{Total energy} - \text{Inaccessible energy}. \tag{2.6}$$

The ambient conditions outside the engine will stretch far enough in order for the equilibrium state not to change from the initial surroundings. This is valid for both temperature, pressure and chemical composition. Therefore, the equilibrium is assumed to be equal to the ambient conditions.

2.2.1 First Law of Thermodynamics

To assess how much of the work potential is lost in each control volume, that here for illustrative purposes can resemble an arbitrary propulsion unit component, a combination of the first and second law of thermodynamics can be used. The first law of thermodynamics for a control volume can be formed using Reynold's transport theorem [11], where B is any extensive property that is conserved and β is the intensive equivalent. The vector velocity $\vec{u}$ is the absolute velocity in perspective of the reference frame and $\vec{u}_{\text{rel.}}$ quantifies the relative velocity to the specific control surface. Reynold's transport theorem is given as

$$\underbrace{\left.\frac{dB}{dt}\right|_{\text{syst.}}}_{\text{Input}} = \underbrace{\frac{\partial}{\partial t}\left(\int_{\text{CV}} \rho\beta dV\right)}_{\text{Change (per time)}} + \underbrace{\int_{\text{CS}} \rho\beta\left(\vec{u}_{\text{rel.}} \cdot \hat{n}\right) dA}_{\text{Flow out minus in}}. \tag{2.7}$$

If the first law of thermodynamics, i.e. conservation of energy, is assessed using the Reynold's transport theorem it yields heat and work, both per unit time, over the system boundary as the input terms on the left-hand side. The intensive quantity β is equal to the total energy per mass denoted with e_0, which is amounts to the internal energy, kinetic energy, and a term collecting other contributions, namely $e + \frac{\|\vec{u}\|^2}{2} + e_{\text{other}}$. Other contributions could cover chemical reactions, nuclear reactions and electrostatic or magnetic field effects. The equation becomes:

$$\dot{Q}_{\text{in}} - \text{P}_{\text{out}} = \frac{\partial}{\partial t}\left(\int_{\text{CV}} \rho e_0 dV\right) + \int_{\text{CS}} \rho e_0 \left(\vec{u}_{\text{rel.}} \cdot \hat{n}\right) dA \tag{2.8}$$

Incoming heat per unit time can be altered to a summation of different heat flows. Work per unit time, i.e. power, can originate from various sources and is typically calculated as the scalar product of the force vector multiplied with the absolute velocity vector. The different forces that act on the system are body forces such as a gravity, fluid forces on the open surfaces of the control volume such as pressure and shear, and reaction forces that can be lumped in specific terms such as shaft work. Inserting these terms for heat and work per unit time into the Reynold's transport theorem equation for energy conservation yields

$$\sum_i \dot{Q}_i - \overbrace{\mathrm{P_S}}^{\text{Shaft}} + \overbrace{\int_{\mathrm{CV}} \rho \vec{f} \cdot \vec{u} dV}^{\text{Body forces}} + \overbrace{\int_{\text{CS open}} \vec{\tau} \cdot \vec{u} dA}^{\text{Shear stress}} - \overbrace{\int_{\text{CS open}} p \left(\vec{u} \cdot \hat{n}\right) dA}^{\text{Pressure}}$$
$$= \frac{\partial}{\partial t} \left(\int_{\mathrm{CV}} \rho e_0 dV \right) + \int_{\mathrm{CS}} \rho e_0 \left(\vec{u}_{\mathrm{rel.}} \cdot \hat{n}\right) dA. \tag{2.9}$$

It can be noted that the pressure power term and the control surface mass flow term share resembling features. It is possible to alternate the expression to get enthalpy which includes the part of the pressure power term originating from the relative velocity. The specific internal energy relates to the enthalpy by $e + \frac{p}{\rho} + \frac{\|\vec{u}\|^2}{2} + e_{\mathrm{other}} = h + \frac{\|\vec{u}\|^2}{2} + e_{\mathrm{other}}$. By using this identity a modified control surface term and pressure power term is obtained. In addition, if the enthalpy reference level is set to the ambient conditions this will quantify the energy difference to the equilibrium state. This is a form that is useful for assessing irreversibility as exergy is quantified as the difference in accessible energy between the true conditions and the equilibrium conditions.

By considering the special case of a propulsion unit it will be possible to neglect several terms based on their magnitude. Gravity is the only body force acting on the mass flow in the system and it is weak in comparison to the other terms. Shear can also be neglected for the same reason, i.e. assumption of inviscid flow. If steady state conditions apply it implies that the flow control volume term can be omitted. Moreover, for the general case of a gas in an aero engine, not considering combustion, the e_{other} term can be left out. The resulting equation taking the enthalpy and the neglected terms into account is

$$\sum_i \dot{Q}_i - \mathrm{P_S} - \int_{\text{CS open}} p \left(\vec{u} - \vec{u}_{\mathrm{rel.}}\right) \cdot \hat{n} dA = \int_{\mathrm{CS}} \rho \left(h - h_\infty + \frac{\|\vec{u}\|^2}{2} \right) \left(\vec{u}_{\mathrm{rel.}} \cdot \hat{n}\right) dA. \tag{2.10}$$

The set of velocity magnitudes C, V and U are commonly used for propulsion units and they quantifies the absolute velocity, relative velocity and flight velocity, respectively, in relation to a reference frame located at the earth surface. These velocities in combination with the assumption of one-dimensional in- and outflows can simplify the expression further. Using a reference frame that is moving with the control volume in combination with the previously mention simplifications yield an expression that is useful for every control volume inside the propulsion unit. The absolute velocity will now equal the relative velocity of the control surface which in turn results in a pressure power term identical to zero. For a finite number of inflows and outflows we obtain:

$$\sum_i \dot{Q}_i - \mathrm{P_S} = \left(\sum_i \dot{m}_i \left[h_i - h_\infty + \frac{V_i^2}{2} \right] \right)_{\mathrm{out}} - \left(\sum_i \dot{m}_i \left[h_i - h_\infty + \frac{V_i^2}{2} \right] \right)_{\mathrm{in}} \tag{2.11}$$

The velocity in the mass flow term is preferred to be expressed using the absolute velocity relative the earth, C, as this quantifies the kinetic energy compared to the equilibrium state with an atmosphere at rest. Rearranging the steady energy flow equation from above so that the velocity relative the earth, C, is used rather than the control volume relative velocity, V, give the addition of a thrust power term, $\mathrm{P_T}$. The new steady state energy equation becomes:

$$\sum_i \dot{Q}_i - \mathrm{P_S} - \mathrm{P_T} = \left(\sum_i \dot{m}_i \left[h_i - h_\infty + \frac{{C_i}^2}{2}\right]\right)_{\text{out}} - \left(\sum_i \dot{m}_i \left[h_i - h_\infty + \frac{{C_i}^2}{2}\right]\right)_{\text{in}} \quad (2.12)$$

where the thrust power term equals

$$\mathrm{P_T} = \left(\sum_i \dot{m}_i \left[\frac{C_i^2}{2} - \frac{V_i^2}{2}\right]\right)_{\text{in}} - \left(\sum_i \dot{m}_i \left[\frac{C_i^2}{2} - \frac{V_i^2}{2}\right]\right)_{\text{out}}. \quad (2.13)$$

Using the velocity definition ($C = U - V$), the expression can be simplified to

$$\mathrm{P_T} = \frac{U}{2}\left(\left[\sum_i \dot{m}_i \left(U - 2V_i\right)\right]_{\text{in}} - \left[\sum_i \dot{m}_i \left(U - 2V_i\right)\right]_{\text{out}}\right). \quad (2.14)$$

Under the assumption of one inflow and one outflow, the equation can be reduced to

$$\mathrm{P_T} = \dot{m}U(V_{\text{out}} - V_{\text{in}}). \quad (2.15)$$

If the exhaust nozzle of the engine is choked, then the pressure difference to the ambient conditions will also contribute to the thrust power. A control volume is now considered that starts at the nozzle exit and stretches far enough to reach the ambient conditions. Using a reference frame fixed to the earth's surface and looking at the pressure power term in Eq.2.10 will result in the pressure power contribution to the thrust power. The positive direction is chosen as the direction of the outflow as this will yield the thrust that is directed backwards so that the engine is pushed forward. If the coordinate system is one-dimensional and aligned with the mass flow the velocities are $\vec{u} = -C$ and $\vec{u}_{\text{rel.}} = V$. This yields the following expression:

$$\mathrm{P}_{\mathrm{T}\text{exhaust}\to\infty} = \sum_i U A_{\text{nozzle-exit},i}\left(p_{\text{exhaust},i} - p_\infty\right). \quad (2.16)$$

Summation of the thrust power terms for each component control volume j included in the propulsion unit during steady state yields

$$\mathrm{P}_{\mathrm{T}\text{prop. unit}} = \sum_j \mathrm{P}_{\mathrm{T},j} = U\left(\begin{array}{c} \left[\sum_i \dot{m}_i V_i\right]_{\text{exhaust}} - \left[\sum_i \dot{m}_i V_i\right]_{\text{intake}} \\ + \sum_i A_{\text{nozzle-exit},i}\left[p_{\text{exhaust},i} - p_\infty\right] \end{array}\right), \quad (2.17)$$

which is equal to the net thrust multiplied with the flight velocity. This expression constitutes the thrust work per unit time of the propulsion unit. Moreover, the velocity in the exhaust is here taken as the true velocity. This would be equal to the thrust coefficient multiplied with the velocity obtained when expanding ideally to the nozzle exit pressure.

2.2.2 Second Law of Thermodynamics

The entropy production term, $\dot{\Pi}$, for a steady state system according to Clausius [12], can be described as:

$$\dot{\Pi} = \left(\sum_i \dot{m}_i s_i\right)_{\text{out}} - \left(\sum_i \dot{m}_i s_i\right)_{\text{in}} - \sum_i \int \frac{dQ_i}{T} \tag{2.18}$$

The entropy reference level is set to the ambient conditions as this will quantify the inaccessible energy difference to the equilibrium state. This will useful as exergy assess the work potential to the equilibrium state. The updated equation becomes:

$$\dot{\Pi} = \left(\sum_i \dot{m}_i \left[s_i - s_\infty\right]\right)_{\text{out}} - \left(\sum_i \dot{m}_i \left[s_i - s_\infty\right]\right)_{\text{in}} - \sum_i \int \frac{dQ_i}{T} \tag{2.19}$$

The Gouy-Stodola theorem [10] states that the irreversibilities of a system is equal to the entropy production multiplied with the equilibrium temperature, i.e.

$$\begin{aligned} \dot{\mathrm{I}} &= T_\infty \dot{\Pi} \\ &= T_\infty \left(\left[\sum_i \dot{m}_i s_i\right]_{\text{out}} - \left[\sum_i \dot{m}_i s_i\right]_{\text{in}} - \sum_i \int \frac{dQ_i}{T} \right), \end{aligned} \tag{2.20}$$

which quantifies generation of new inaccessible energy on a power unit basis.

2.2.3 Combining the First and Second Law of Thermodynamics

A mass specific measure of the work potential illustrated in Eq.2.6 is formed when combining the specific total enthalpy and specific entropy multiplied with the equilibrium temperature, i.e. the ambient temperature. This yields the specific exergy, it is

$$\underbrace{\epsilon}_{\text{Work potential}} = \underbrace{\Delta h + \frac{C^2}{2}}_{\text{Total energy}} - \underbrace{T_\infty \Delta s}_{\text{Inaccessable energy}} . \tag{2.21}$$

An expression for the irreversibility of a control volume is obtained from the steady state energy equation and the irreversibility expression from the second law of thermodynamics, both for a steady state control volume and expressed by Eq.2.12 and Eq.2.20, respectively. Arranging it so that the specific exergy terms are collected on the right-hand side yields:

$$\sum_i \dot{Q}_i - \mathrm{P_S} - \mathrm{P_T} - T_\infty \sum_i \int \frac{dQ_i}{T} - \dot{\mathrm{I}} =$$

$$\left(\left[\sum_i \dot{m}_i \left(h_i - h_\infty + \frac{{C_i}^2}{2} \right) \right]_{\text{out}} - \left[\sum_i \dot{m}_i \left(h_i - h_\infty + \frac{{C_i}^2}{2} \right) \right]_{\text{in}} \right)$$

$$-T_\infty \left(\left[\sum_i \dot{m}_i \left(s_i - s_\infty \right) \right]_{\text{out}} - \left[\sum_i \dot{m}_i \left(s_i - s_\infty \right) \right]_{\text{in}} \right) \tag{2.22}$$

The shaping of the irreversibility expression is continued by exchanging the specific enthalpy and entropy to form the specific exergy detailed in Eq.2.21 and combining the heat flow terms into one term. In addition, arranging the terms so that the irreversibility is alone on the left-hand side yields

$$\dot{\mathrm{I}} = \left(\sum_i \dot{m}_i \epsilon_i \right)_{\text{in}} - \left(\sum_i \dot{m}_i \epsilon_i \right)_{\text{out}} - \mathrm{P_S} - \mathrm{P_T} + \sum_i \int_{\text{start}}^{\text{end}} \frac{T - T_\infty}{T} d\dot{Q}_i,$$

which was presented in Eq.2.2.

The energy terms from the first law are conserved in the expression. Only the second law will add to the irreversibility. The irreversibility detailed for the second law is quantifying the lost work potential in the exergy equation. Three interesting aspects of exergy analysis can be directly related to this expression. The first and primary observation is that the irreversibilities, or exergy destruction, on a power unit is nothing but the entropy production multiplied with a reference temperature. No additional insight is needed of the underlying exergy loss sources than from what is known from entropy production. Secondly, knowing the difference in entropy and the heat transfer for a control volume is enough to calculate the irreversibility of the same control volume. Thirdly, monitoring and analyzing entropy production is a common method for aero engine turbomachinery component analysis. Such analysis can be seen as nothing but an implicit use of the exergy methodology as the entropy production term is directly related to the irreversibility through the multiplication with a reference temperature.

The exergy balance equation in Eq.2.2 needs further explanation of the included terms. The heat transfer term and the specific exergy equation are both detailed below. The shaft power is simply the work per unit time from a mechanical shaft, i.e. angular velocity multiplied with torque.

Without detailed knowledge of the heat transfer process the term needs to be simplified in order to be implemented in a propulsion unit performance code. In case of the assumption of a perfect gas, using $d\dot{Q}_i = c_{\mathrm{p},i} \dot{m}_i dT_i$ and $\dot{Q}_i = c_{\mathrm{p},i} \dot{m}_i \left(T_{i,\text{end}} - T_{i,\text{start}} \right)$ the heat transfer integral can be rewritten according to

$$-\sum_i \int_{\text{start}}^{\text{end}} \frac{T - T_\infty}{T} d\dot{Q}_i = -\sum_i \frac{d\dot{Q}_i}{dT} \int_{T_{i,\text{start}}}^{T_{i,\text{end}}} \frac{T - T_\infty}{T} dT \tag{2.23}$$

$$= -\sum_i \dot{Q}_i \left(1 - T_\infty \frac{\ln\left[T_{i,\text{end}}/T_{i,\text{start}}\right]}{\left[T_{i,\text{end}} - T_{i,\text{start}}\right]} \right). \tag{2.24}$$

If the temperature is, or can be approximated as constant during the heat transfer, the heat transfer integral in Eq.2.2 simplifies according to

$$-\sum_i \int \frac{T - T_\infty}{T} d\dot{Q}_i = -\sum_i \dot{Q}_i \frac{T_i - T_\infty}{T_i}. \tag{2.25}$$

This is also consistent when taking the limit of Eq.2.24.

The specific exergy introduced in Eq.2.21 is further detailed and written on an ideal form in Eq.2.26. Mixing does only affect the entropy term when an ideal gas is considered. The specific exergy includes the different forms of exergy that are applicable to a flying aero engine, i.e. a thermomechanical part and a chemical part. The potential energy for the gas mass flow can be neglected. The thermomechanical part is here divided in two terms; one that includes all contribution except the kinetic energy and another to account for the kinetic part. The specific exergy equation becomes

$$\varepsilon = \underbrace{h - h_\infty - T_\infty(s_{\text{th.}} - s_{\text{th.},\infty})}_{\text{thermomechanical excl. kinetic}} + \underbrace{\frac{C^2}{2}}_{\text{kinetic}} + \underbrace{T_\infty\left(s_{\text{mixing}} - s_{\text{mixing},\infty}\right)}_{\text{chemical}}. \tag{2.26}$$

The thermomechanical part is different from zero as long as the temperature, pressure and velocities are different from the ambient conditions. This term is also known as the physical term but since the use of the word thermomechanical more clearly describes the term's origin it is the preferred convention in this work. The kinetic exergy is just the kinetic energy of the current state since the gas when brought to equilibrium with the ambient conditions will be at rest. The "thermomechanical excluding kinetic exergy" term includes entropy contributions denoted with th for thermomechanical, which implies that the mixing effect is not included in the term.

The entropy of mixing does instead constitute the chemical term in the exergy equation. It is possible to calculate the exergy of mixing by assessing the difference in Gibbs free energy for the true gas composition to the equilibrium gas composition, both evaluated at ambient temperature and pressure. The mixing exergy does originate from different partial pressures from the ambient conditions. Dalton's law states that the partial pressure is proportional to the mole fraction. Only the gas downstream of the combustion will have different gas proportions than the ambient conditions and consequently the chemical exergy term will only be different from zero after the combustion has taken place.

The total entropy of mixing on a joule per kelvin unit associated with the mixing of the gas composition of the ambient conditions and an amount of gas flow mass, $m_{\text{aero engine gas}}$, that under a given moment is in an arbitrary component downstream of the combustion process, can be calculated via

$$\begin{aligned}\Delta S_{\text{mixing}} = &\underbrace{\left(\left[-m\sum_i y_i R_i \ln x_i\right]_{\text{aero engine gas}} + \left[-m\sum_i y_i R_i \ln x_i\right]_{\text{ambient air}}\right)}_{\text{before mixing}} \\ &- \underbrace{\left(\left[-m\sum_i y_i R_i \ln x_i\right]_{\text{aero engine gas}} + \left[-m\sum_i y_i R_i \ln x_i\right]_{\text{ambient air}}\right)}_{\text{after mixing}}, \end{aligned} \tag{2.27}$$

where R is the specific gas constant, and y and x corresponds to the mass- and mole fraction, respectively. Since mass is conserved between the states the formulation can be altered to:

$$\begin{aligned}\Delta S_{\text{mixing}} = &\left(-m\sum_i y_i R_i \ln \frac{x_{i,\text{before mixing}}}{x_{i,\text{after mixing}}}\right)_{\text{gas aero engine}} \\ &+ \left(-m\sum_i y_i R_i \ln \frac{x_{i,\text{before mixing}}}{x_{i,\text{after mixing}}}\right)_{\text{ambient air}} \end{aligned} \tag{2.28}$$

We assume that the ambient conditions stretches significantly far away that the composition after mixing of the aero engine gas flow mass and the ambient conditions is no different from the initial composition at the ambient conditions. For the gas flow aero engine terms this bring the following change:

$$\begin{aligned}\Delta S_{\text{mixing}} = &\left(-m\sum_i y_i R_i \ln \frac{x_{i,\text{before mixing}}}{x_{i,\infty}}\right)_{\text{aero engine gas}} \\ &+ \left(-m\sum_i y_i R_i \ln \frac{x_{i,\text{before mixing}}}{x_{i,\text{after mixing}}}\right)_{\text{ambient air}} \end{aligned} \tag{2.29}$$

When considering the specific exergy associated with the engine gas flow it implies that the upper row of the formula is considered, it is

$$\Delta s_{\text{mixing, aero engine gas}} = -\sum_i y_i R_i \ln \frac{x_i}{x_{i,\infty}}.$$

This can be introduced in the specific exergy equation to form

$$\varepsilon = \underbrace{h - h_\infty - T_\infty(s_{\text{th.}} - s_{\text{th.},\infty})}_{\text{thermomechanical excl. kinetic}} + \underbrace{\frac{C^2}{2}}_{\text{kinetic}} + \underbrace{T_\infty\Big(\sum_i \lambda_i R_i \ln\frac{x_i}{x_{i,\infty}}\Big)}_{\text{chemical}}. \tag{2.30}$$

Aero engine performance simulations are commonly made using zero relative humidity. To allow for proper exergy calculations the relative humidity needs to be set different from zero when using Eq.2.30 as the chemical term relies on the exhaust species to also exist in the ambient conditions. This is because the ambient conditions are assumed to stretch far enough so that the different gas composition in the engine will not affect the surroundings. It shall be noted that the mixing entropy for the total assessment of both the aero engine gas mass and ambient air mass would effectively be zero in Eq.2.29. Using the assumption that the ambient conditions stretches far enough to be unchanged after mixing also leads to the consequence that $m_{\text{aero engine gas}}/m_{\text{ambient air}}$ becomes infinitely small which cancels the aero engine gas term as $\lim_{\xi\to 0}\xi\ln(\xi) = 0$ for an arbitrary variable ξ.

2.3 Fuel Exergy

Fuel exergy is equivalent to the work potential found between the state of unburned fuel and the state when burned fuel and the reference environment are in complete equilibrium with each other. During the combustion process the species in the fuel mixture react with oxygen and other new species are formed while the difference in enthalpy of formation is released as heat. The chemical component in the standard exergy equation described in Eq.2.30 originates from the entropy of mixing and not the chemical reaction. A method that can be used to evaluate exergy during a chemical reaction, by including the release of enthalpy and entropy looked in the chemical composition, is described in detail by Kotas [13]. The equation is

$$\varepsilon_{\text{fuel}} = \varepsilon_{\text{fuel,thermomechanical excl. kinetic}} + \varepsilon_{\text{fuel,kinetic}} + \varepsilon_{\text{fuel,chemical}}, \tag{2.31}$$

where the subcomponents are calculated by the following formulas

$$\begin{aligned}
\varepsilon_{\text{fuel,thermomechanical excl. kinetic}} &= \left(\sum_i \beta_i\left[h_i - h_{\text{ss},i}\right] - \sum_i \lambda_i\left[h_{\infty,i} - h_{\text{ss},i}\right]\right) \\
&\quad - T_\infty\left(\sum_i \beta_i\left[s_i - s_{\text{ss},i}\right] - \sum_i \lambda_i\left[s_{\infty,i} - s_{\text{ss},i}\right]\right), \\
\varepsilon_{\text{fuel,kinetic}} &= \sum_i \beta_i\frac{C_i^2}{2} \text{ and} \\
\varepsilon_{\text{fuel,chemical}} &= \sum_i (\beta_i - \lambda_i)\cdot\left(\Delta h^\circ_{\text{f},i} - T_\infty \Delta s^\circ_{\text{f},i}\right),
\end{aligned}$$

of which β_i = mass proportion of constituent i in fuel,
λ_i = mass of combustion product of constituent i per unit burned fuel,
$\Delta h^\circ_{\mathrm{f},i}$ = standard enthalpy of formation for constituent i and
$\Delta s^\circ_{\mathrm{f},i}$ = standard entropy of formation for constituent i.

It is worth noting that fuel exergy is not equal to the LHV nor the HHV value even though it will be quite similar in magnitude. Fuel exergy as opposed to LHV and HHV does also include a couple of additional contributing terms aside from the heat of combustion. Heat of combustion is calculated as the difference of heat of formation between the products and the reactants. Heat of formation is corresponding to the difference in enthalpy of a compound compared to its constituent elements at standard state temperature and pressure. This implies that it quantifies the amount of enthalpy locked into the chemical composition. The heat of combustion is included in the chemical fuel exergy term as the summation of the heat of formation terms. Entropy of formation is, in addition to the heat of formation, also included in the chemical fuel exergy term. This term reflects upon the case that entropy for the species after a combustion is much larger than the for the reactants, i.e. heat is captured by the products. The chemical fuel exergy term is much larger than the thermomechanical fuel exergy, and the heat of combustion constitutes the dominating part of the chemical fuel exergy.

The difference in enthalpy and entropy when comparing the thermomechanical state of the fuel at rest to the ambient conditions for the combustion products is included in the "thermomechanical excluding kinetic exergy" term. This reflects upon the work potential inherently present in the different pressure and temperature for the unburned fuel compared to the ambient conditions. The kinetic exergy is left unchanged compared to the standard formulation expressed in Eq.2.30 as the change of species between the true conditions and the reference does not affect the term.

The method described in Eq.2.31 to calculate fuel exergy requires full knowledge of the fuel composition. Jet propulsion fuel, or more specifically Jet A in the case of commercial aviation, is a mixture of various hydrocarbons which therefore becomes less straight forward to model. However, even without knowledge of the full composition it is possible to a large extent to make use of what is commonly included in many engine performance modeling tools. The heat of combustion term in the chemical fuel exergy can be quantified as the LHV value for the specific fuel mixture.

It could be questioned whether it would be the most accurate to use LHV or HHV to assess the heat of combustion. The effective difference between LHV and HHV is the heat of vaporization, where the first heating value considers any formed water during combustion as vapor as opposed to the latter where liquid is assumed. The appropriate choice for the heat of combustion term is dependent on whether the ambient conditions implies that the air is saturated with vapor or not. In case of ambient conditions including air saturated with vapor the water formed during the combustion process will condense when brought to equilibrium with its surroundings, if the relative humidity instead is lower than 100% the same exhaust water will remain as vapor. Aero engine performance simulations are usually made at a low relative humidity, and thus LHV is the appropriate choice. Using the enthalpy of formation for the water as vapor is also consistent with the implementation by Horlock and Clark [1].

The thermomechanical enthalpy contribution from the fuel can be assessed using the temperature dependent tables that are included to incorporate the fuel energy difference corresponding to a fuel temperature different from the standard state temperature. Enthalpy is not dependent on pressure for liquids, and therefore the effect of a different pressure than the standard state does not need to be incorporated in the analysis. Entropy of formation nor entropy temperature tables are on the other hand not commonly available in the aero engine performance codes. The combustion modeling code Chemical Equilibrium and Applications [15], developed by NASA, is using $C_{12}H_{23}$ as representative of Jet A. Hence, fuel entropy of formation as well as fuel thermomechanical entropy can be assumed as the values corresponding to $C_{12}H_{23}$. The post-combustion species are common substances, and can be found in a reference containing tabulated thermodynamic data [14] or be modeled using polynomials described by McBride and Gordon [15].

In the case of modeling fuel exergy of Jet A the different terms become

$$
\begin{aligned}
\varepsilon_{\text{JetA,thermomechanical excl. kinetic}} &= [h - h_{\text{ss}}]_{\text{fuel-table}} \\
&\quad - \sum_i \lambda_i \left[h_{\infty,i} - h_{\text{ss},i}\right] \\
&\quad - T_\infty \left([s - s_{\text{ss}}]_{\mathrm{C_{12}H_{23}}} - \sum_i \lambda_i \left[s_{\infty,i} - s_{\text{ss},i}\right] \right), \\
\varepsilon_{\text{JetA,kinetic}} &= \frac{C_{\text{fuel}}^2}{2} \text{ and} \\
\varepsilon_{\text{JetA,chemical}} &= \text{LHV} - T_\infty \left(\Delta s^\circ_{\text{f},\mathrm{C_{12}H_{23}}} - \sum_i \lambda_i \Delta s^\circ_{\text{f},i} \right).
\end{aligned}
$$

2.3.1 Fuel Exergy Combustion Modeling

Combustion in the ideal circumstances balances fuel reactants with oxidants, and generate only a limited number of products, i.e. complete combustion is considered. In a real case it is likely that some of the fuel reactants only partially react with the oxygen during the combustion process. These elements will then consequently stay unburned or remain as non-ideal products in the exhaust flow. Combustion at very high temperatures might also cause dissociation of the reaction products, a more general formulation in this case is the assumption of chemical equilibrium rather than complete combustion. Both incomplete combustion as well as dissociation are resulting in lower flame temperatures than during complete combustion. Fuel exergy is no different from exergy in general as it quantifies the work potential. Hence, complete combustion must always be considered in terms of quantifying fuel exergy. This is also true in cases where the real combustion process is incomplete as well as in existence of dissociation of the combustion products. Rather than considering these irregularities as a cause for lowering the work potential they should be regarded as irreversibilities of the combustion process.

Complete combustion is assessed by balancing the number of atoms in the reactants with the products, assuming only water and oxides of the non-hydrogen atoms among the products. Fuel can consist of many different elements, here the general case of a fuel molecule consisting of carbon, hydrogen, sulfur, oxygen and nitrogen is considered. Among the fuel elements that react with the oxide the following is true; carbon will yield carbon dioxide, hydrogen will yield water and sulfur will yield sulfur dioxide. Oxygen in the fuel will lower the amount of the required external oxidant. Nitrogen does not under ideal conditions yield any nitrogen oxide as the heat of formation is lower for the separate constituents. The general formula balancing the elements becomes

$$C_aH_bS_cO_dN_e+(a+\frac{b}{4}+c-\frac{d}{2})O_2 \xrightarrow{\text{Combustion}} aCO_2+\frac{b}{2}H_2O+cSO_2+\frac{e}{2}N_2+\text{heat}. \tag{2.32}$$

Calculating the mass proportion of a constituent in the fuel, β_i and the mass of combustion product per unit burned fuel, λ_i, for a fuel mixture consisting of multiple types of fuel molecules is possible when using the statement above for each and every one of the fuel molecules. The mass proportions of the different fuel molecules are described by $y_{\text{fuel},i}$. The expressions become:

$$\begin{array}{r|cc}
 & \beta_i & \lambda_i \\
\hline
[C_{a_1}H_{b_1}S_{c_1}O_{d_1}N_{e_1}]_1 & y_{\text{fuel},1} & 0 \\
\vdots & \vdots & \vdots \\
[C_{a_n}H_{b_n}S_{c_n}O_{d_n}N_{e_n}]_n & y_{\text{fuel},n} & 0 \\
O_2 & 0 & -\sum_{i=1}^{n} y_{\text{fuel},i}\frac{M_{O_2}}{M_{\text{fuel}}}\,(a_i+\frac{b_i}{4}+c_i-\frac{d_i}{2}) \\
CO_2 & 0 & \sum_{i=1}^{n} y_{\text{fuel},i}\frac{M_{CO_2}}{M_{\text{fuel}}}\,a_i \\
H_2O & 0 & \sum_{i=1}^{n} y_{\text{fuel},i}\frac{M_{H_2O}}{M_{\text{fuel}}}\,\frac{b_i}{2} \\
SO_2 & 0 & \sum_{i=1}^{n} y_{\text{fuel},i}\frac{M_{SO_2}}{M_{\text{fuel}}}\,c_i \\
N_2 & 0 & \sum_{i=1}^{n} y_{\text{fuel},i}\frac{M_{N_2}}{M_{\text{fuel}}}\,\frac{e_i}{2}
\end{array} \tag{2.33}$$

Jet A consists of a mixture of many hydrocarbons that all have carbon numbers ranging between 8 and 16 [16]. The mass composition of the hydrocarbons in the fuel is however not known, which results in that the general formula from above cannot be used. Another way must be found. One option could be using $C_{12}H_{23}$ as representative of Jet A in line with the combustion code Chemical Equilibrium and Applications, which previously also have been applied by the author of this thesis [7]. Another way could be looking at the mass composition of the single elements in the fuel. In the case of the general fuel molecule this requires the mass proportions of the five elements. In case of a pure hydrocarbon the number of elements reduces to two. This approach can yield the composition of the products but it will not be useful trying to compute heat of combustion as the composition of the reactants is unknown. For Jet A it is not necessary to know the composition of the reactants since they can be accounted for by other means in the fuel exergy assessment. In short, the LHV value and the enthalpy tables can be used in combination with the assumption that the composition of $C_{12}H_{23}$ is representative for Jet A to evaluate the less dominant entropy fuel exergy terms.

Assuming that the mass proportions of the different elements in the fuel are known the reaction products can be assessed by altering the method from above. The expressions become:

$$
\begin{array}{r|c}
 & \lambda_i \\
\hline
\left[\begin{array}{r} Cy_{\text{fuel},C} + Hy_{\text{fuel},H} + Sy_{\text{fuel},S} \\ + Oy_{\text{fuel},O} + Ny_{\text{fuel},N} \end{array}\right] & 0 \\
O_2 & y_{\text{fuel},O} - \left(\frac{x_{\text{fuel},C}}{M_C} + \frac{x_{\text{fuel},H}}{4M_H} + \frac{x_{\text{fuel},S}}{M_S}\right) M_{O_2} \\
CO_2 & y_{\text{fuel},C}\frac{M_{CO_2}}{M_C} \\
H_2O & y_{\text{fuel},H}\frac{M_{H_2O}}{2M_H} \\
SO_2 & y_{\text{fuel},S}\frac{M_{SO_2}}{M_S} \\
N_2 & y_{\text{fuel},N}
\end{array}
\tag{2.34}
$$

2.4 Installation Effects on Exergy

The net thrust generated by the engine is propelling the aircraft. As long as the aircraft does not accelerate the forces that act on the aircraft must be in equilibrium with each other. This means that the net thrust is compensating for the drag of the aircraft. Utilizing the thrust required to compensate for any subsystem or component of the aircraft gives an opportunity to assess the impact a component or a subsystem has on the cycle. These forces multiplied with the flight velocity will correspond to the thrust power, or thrust work per unit time, that the propulsion unit is required to generate in order for the aircraft to stay on path. From Eq.2.17 it can be seen that the thrust power generated by the propulsion cycle equals the net thrust force multiplied with the flight velocity. When adding up the thrust power required to compensate for all the aircraft components that have weight and causes direct drag this will in steady state match the thrust power generated by the propulsion cycle. It is worth remembering that the only work produced from an aircraft system perspective is the change in altitude, all other power that originates from the fuel will be used to compensate for the direct drag, lift caused drag and other irreversibilities of the aircraft system.

To assess the impact of the drag and weight one must start by balancing the forces that act on the engine. A schematic of the acting forces and the axes for a generic aircraft is provided in Fig.2.2. The angle between the aircraft axis and the aerodynamic axis is the angle of attack the aircraft has towards the air, α. The aerodynamic axis is parallel to the trajectory of the aircraft. The attitude, θ, is corresponding to the angle the aircraft has towards the horizontal plane. The climb gradient, γ, is instead the angle that the aircraft is moving in compared to the horizontal plane. The propulsion unit is mounted with an angle δ to the aircraft axis, the axis made up by δ will be in line with the direction of the thrust. Lift is perpendicular and drag is parallel to the aerodynamic axis of the aircraft. The weight force will act in the direction of the vertical axis.

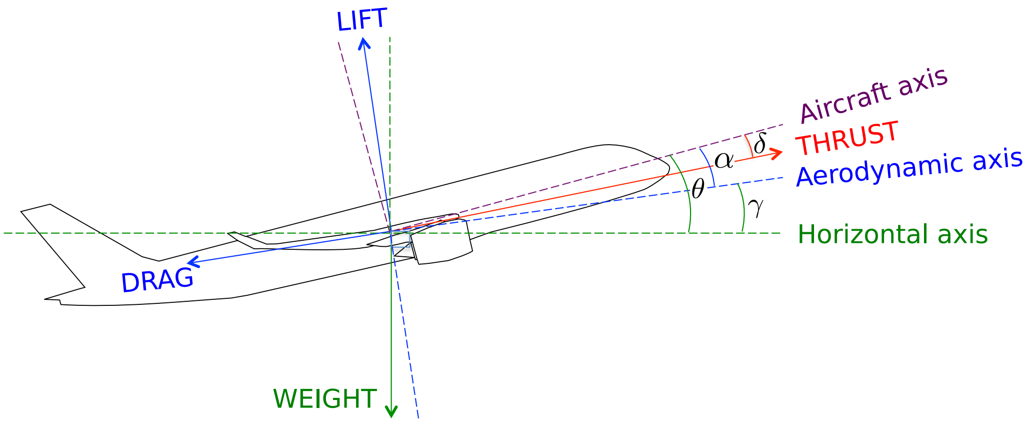

Figure 2.2: *Main forces acting on an aircraft and its main directions.*

The force balances in the direction parallel to and the direction perpendicular to the flight trajectory become

$$\begin{aligned} ma_D &= -D + T\cos(\alpha-\delta) - mg\sin(\gamma) \text{ and} \\ ma_L &= L + T\sin(\alpha-\delta) - mg\cos(\gamma). \end{aligned} \tag{2.35}$$

The analysis is intended to yield a power balance, i.e. work per unit time. Work is assessed as the force applied in the trajectory direction multiplied with the object velocity and integrated over time. The drag equation is summing up the forces in the direction of the object trajectory. If a L/D number is assumed to be known the drag term can be altered accordingly

$$ma_D = -\frac{L}{L/D} + T\cos(\alpha-\delta) - mg\sin(\gamma). \tag{2.36}$$

Using the lift equation in Eq.2.36 gives

$$
\begin{aligned}
ma_D &= -\frac{m\,(a_L + g\cos(\gamma)) - T\sin(\alpha-\delta))}{L/D} + T\cos(\alpha-\delta) - mg\sin(\gamma) \\
&= T\cos(\alpha-\delta) + \frac{T\sin(\alpha-\delta)}{L/D} - mg\sin(\gamma) - \frac{m(a_L + g\cos(\gamma))}{L/D}. \qquad (2.37)
\end{aligned}
$$

Rearranging the equation gives the thrust term on one side and the mass terms on the other. The force in the velocity direction times the velocity itself can be assessed using a scalar product of the respective vectors in the general work equation integrated over time. A scalar product of two vectors can be computed as the multiplication of the vector magnitudes and the cosine function of the angle between the vectors. With this in mind it can be seen as ambiguous that there is both a cosine function as well as another term on the left-hand side. It should then be noted that these contributions actually originate from two different forces. The cosine term is the direct influence from the thrust in the direction of the flight trajectory. The other term corresponds to the force perpendicular to the flight trajectory, in the direction of the lift, which alters the required lift that in turn affects the drag. This term shall however not be seen as drag directly caused by lift. Drag originates from a combination of drag sources and lift over drag includes both drag from lift as well as drag present without considering lift.

$$
T\left(\cos(\alpha-\delta) + \frac{\sin(\alpha-\delta)}{L/D}\right) = m\left(a_D + \frac{a_L}{L/D} + g\sin(\gamma) + \frac{g\cos(\gamma)}{L/D}\right) \qquad (2.38)
$$

Multiplication of the flight velocity on both sides gives the equation on a power unit. The left-hand side can be split up in two terms. One of the terms equals the thrust power generated by the propulsion unit and the other quantifies the loss due to misalignment between the thrust and the flight direction. This right-hand side can be divided into two parts: a dissipating and a non-dissipating and hence exergy accumulating part. The steady state contribution of the non-dissipative part is accumulated as potential power in climb and can later on be harvested during descent. The acceleration terms will add to the momentum and are by definition non-dissipative.

$$
\begin{aligned}
UT\left(\underbrace{1}_{\substack{\text{fully aligned}\\ \text{propulsion unit}}} - \underbrace{\left[1 - \left(\cos(\alpha-\delta) + \frac{\sin(\alpha-\delta)}{L/D}\right)\right]}_{\text{misalignment}}\right) &= \\
mU\left(\underbrace{a_D + \frac{a_L}{L/D}}_{\text{acceleration}} + \underbrace{g\sin(\gamma)}_{\text{potential}} + \underbrace{\frac{g\cos(\gamma)}{L/D}}_{\text{dissipative}}\right) & \qquad (2.39)
\end{aligned}
$$

The terms on the left-hand side above can be exchanged into thrust power terms, it is

$$P_{T,ideal} = P_{T,prop.\ unit} - P_{T,misalign.}. \tag{2.40}$$

Multiple sources of drag exist in the the context of an aircraft. Drag can be divided into three different groups, they are profile drag, induced drag and wave drag. Profile drag includes skin friction drag, form drag and interference drag. The sources originate from the forces due to skin friction, the pressure distribution over the aircraft body and the mixing of streamlines over the body. Wave drag is the drag created from shock waves and is therefore only present in either transonic or supersonic flight. The induced drag originate from vortices that are created on the tip of the wing that in turn change the angle of attack which creates more drag. These drag sources will partly originate from lift while the other part will be present independent from the current lift force. It is a common practice to divide the drag equation into one contribution that is independent of lift and another that is a function of lift. All the contributing groups of the drag mentioned above have a part due to lift. Induced drag is only due to lift while the profile and wave drag have contributing parts that are either a functions of, or independent of lift.

An arbitrary aircraft component or a subsystem could by itself add lift and drag in various ways. Such analysis might become complicated when one starts to consider where to put the boundary of each component as the aircraft consists of a large number of integrated components. It also becomes a question of how the weight of one component should be matched to the corresponding drag force. Roth and Mavris included an aircraft loss breakdown over a mission profile, in terms of a technology assessing availability method named gas horse power. The wave drag, skin friction and form drag over the fuselage, the tails and the external equipment stores of a F-5E fighter jet were considered [17, 18]. The analysis also assessed the wings that in addition to the loss sources of the other components also included induced drag and lift. Different standards exist in aircraft design that allocate component weights into groups that correspond to a much more detailed breakdown of the weights than wings, fuselage, tails and external equipment stores. Such a standard could be used for an in-depth installed exergy analysis but would require an extensive effort attributing the drag loss source to the right component. Roth also introduced the idea of distributing the corresponding fuel loss to the weight of each component [19]. This idea could be developed further in the frame of exergy analysis by charging the additional thrust power required to carry the weight of the fuel corresponding to the different component irreversibilities as part of the component losses themselves.

Paulus and Gagglioi extended the installed exergy analysis by assessing the exergy of lift in subsonic flight [20]. The exergy of lift is relying on the minimum drag associated with the lift to stay at constant altitude for a component with an associated weight. The minimum drag corresponding to the weight that the wings are supposed to carry are not seen as an irreversibility of the wings but rather attributed to the different components weights. Such analysis would require information about the aircraft wing surface area and aspect ratio. It could be discussed which drag loss allocation scheme to carry a weight is the most appropriate. Paulus and Gagglioi allocate only the minimum drag lift to each weight while it could be considered that a certain component with a given weight would, if the weight was altered, affect the lift requirement more than just the minimum drag associated with the weight change. Such change would affect drag that is not dependent on lift since a wing that is not generating lift is still causing drag at a wing angle of attack at zero. Furthermore, a potential weight change would also affect the drag associated with the non ideal lift caused drag. Note that an analysis that allocate all the losses associated with a component weight to the component will also require full knowledge about the total lift caused drag. Which allocation to use becomes a matter of perspective, both allocation schemes will most likely yield different interesting insights of the system.

If one instead would see the geometrical shape of all components necessary for the aircraft this could allow an analysis dependent only on weight. Using Eq.2.39 for an independent component or subsystem implies assessment of the impact based on the weight that needs to be compensated for by the propulsion unit. The impact of each component is then assumed to correspond to their weight averaged share of the total thrust requirement as the lift over drag number is taken as the aircraft metric. This would allow for an analysis that requires less information about the aircraft as a whole which could be useful when only analyzing a component or subsystem. It could also be possible to combine this analysis with the assessment of the independent drag power if such information is known. This would however require the analysis to be altered slightly as the drag from the component itself is included in the total lift to drag ratio number.

2.4.1 Aero Propulsion System Exergy Assessment

The full performance of the propulsion subsystem is not only the thrust generated from the propulsion unit. The propulsion subsystem has the main purpose of generating thrust towards the aircraft. The thrust required to compensate for the fact that the propulsion subsystem adds weight and causes additional drag for the aircraft is not beneficial for the aircraft system in terms of transporting wings, fuselage, fuel, passengers and cargo. Hence, these irreversibilities should be included as irreversibilities of the propulsion unit in a system assessment. This yields an analysis that considers the full performance of the propulsion unit rather than the performance of the thermodynamic cycle itself.

If the drag directly associated with the propulsion system is possible to evaluate the force quantity it yields can be used for computing the power drag associated with the propulsion subsystem. Here we consider a propulsion unit clearly separated from the wings and body of the aircraft. The drag power, as the drag force is in the negative direction of the flight trajectory, can be estimated accordingly:

$$\mathrm{P}_{\mathrm{D,prop.\ syst.}} = -UD \tag{2.41}$$

The balance of a single drag force and the thrust required to compensate for it yields the following expressions in Eq.2.42 and Eq.2.43. The first is including the misalignment of thrust with the flight trajectory while the second disregards misalignment and assumes that it is included in another thrust power term.

$$
\begin{aligned}
\mathrm{P}_{\text{T,prop. syst.-D incl. misalign.}} &= \frac{1}{\cos(\alpha-\delta)} U D && (2.42)\\
\mathrm{P}_{\text{T,prop. syst.-D excl. misalign.}} &= U D && (2.43)
\end{aligned}
$$

The drag caused by a conventional ducted fan engine would mainly be made up by the nacelle drag. It is also possible to include drag from the pylon in the analysis even though it would have a smaller impact.

If the lift caused drag associated with the weight could be estimated it would be possible to use the thrust power drag equations detailed above. This would lead to an exact assessment of the thrust power required to compensate for the weight of the propulsion system. However, such analysis would require extensive information about the aircraft wings which in many cases is not known in a propulsion system performance assessment.

The weight caused drag associated with the propulsion system can also be seen as the weight normalized share of the drag using Eq.2.39. Using the direct engine drag in combination with the weight normalized drag from engine would be analogous to the installed specific fuel consumption formula, namely

$$
\mathrm{SFC}_{\text{installed}} = \frac{\dot{m}_{\text{fuel}}}{T_{\text{net}-D_{\text{nacelle}}-D_{\text{from engine weight}}}}, \tag{2.44}
$$

where the drag caused by the engine weight is

$$
D_{\text{from engine weight}} = \frac{m_{\text{engine}} g}{L/D_{\text{aircraft without nacelle}}}. \tag{2.45}
$$

It shall be noted that the lift over drag number should ideally be altered in the weight thrust power equation to exclude the propulsion system drag in the denominator as the direct propulsions system drag is already compensated for in Eq.2.42. However, the drag for the propulsion system is expected to be significantly lower than the total drag. In addition, the terms in Eq.2.39 that include the lift over drag number have a rather small impact on the equation. With this in mind the lift over drag number could be assumed as the true aircraft value.

The formulations for the thrust power to compensate for the propulsive system weight are detailed in Eq.2.46 and Eq.2.47. The first equation includes misalignment of thrust with the flight trajectory and the second disregards misalignment and assumes it to be included in another thrust power term.

$$\mathrm{P}_{\mathrm{T,prop.\ syst.\text{-}W\ incl.\ misalign.}} = \frac{U m_{\mathrm{prop.\ syst.}}}{\cos(\alpha-\delta)+\frac{\sin(\alpha-\delta)}{L/D}} \left(a_D + \frac{a_L}{L/D} + g\sin(\gamma) + \frac{g\cos(\gamma)}{L/D}\right) \tag{2.46}$$

$$\mathrm{P}_{\mathrm{T,prop.\ syst.\text{-}W\ excl.\ misalign.}} = U m_{\mathrm{prop.\ syst.}} \left(a_D + \frac{a_L}{L/D} + g\sin(\gamma) + \frac{g\cos(\gamma)}{L/D}\right) \tag{2.47}$$

It should be noted that the sinus term in the misalignment factor could be omitted as it is at least two orders of magnitude smaller than the cosine term for a conventional aircraft.

The weight to compensate for a conventional aero engine would be the engine itself and the pylon holding the engine. It shall be noted that engine weight is not only a burden for the system since it also contributes to wing load alleviation. This is however a secondary effect which is complex to assess. It could also be possible to include the fuel weight associated with the irreversibilities of the propulsion system.

The potential energy stored during climb is not lost for the system, instead it can be harvested in descent to lower the thrust requirement to stay on path. Due to this difference towards the other terms of the weight thrust power equation, it will be denoted

$$\mathrm{P}_{\mathrm{T,prop.\ syst.\text{-}D\ stored\ pot.}} = \begin{cases} U m_{\mathrm{prop.\ syst.}} g\sin(\gamma) & \text{if } \gamma > 0 \\ 0 & \text{if } \gamma \leq 0 \end{cases}. \tag{2.48}$$

When the aircraft is in descent the potential exergy term is turning negative, this implies that the exergy that was stored as potential energy during climb is now harvested. The term becomes

$$\mathrm{P}_{\mathrm{T,prop.\ syst.\text{-}D\ harvested\ pot.}} = \begin{cases} 0 & \text{if } \gamma > 0 \\ U m_{\mathrm{prop.\ syst.}} g\sin(-\gamma) & \text{if } \gamma \leq 0 \end{cases}. \tag{2.49}$$

2.4.2 Installed Rational Efficiency

A new term, installed rational efficiency was proposed by Thulin et al. [7], to assess the full impact of the propulsion subsystem as a means to produce thrust for the aircraft. An equation to constitute the following pseudo equation was sought

$$\Psi_{\mathrm{syst.,inst.}} = \frac{\text{Useful thrust power for the aircraft}}{\text{Consumed exergy}}. \tag{2.50}$$

The useful power generated by the aero engine is the thrust it provides to the aircraft as well as the bleed and power it potentially supplies to the cabin. Compared to the rational efficiency in Eq.2.5 the installed rational efficiency also takes the drag and the weight associated with the propulsion system into account.

It could be debated whether the misalignment between the propulsion system and the flight trajectory should be considered separately from the propulsion system or not. For a conventional engine, contrary to a unit with a thrust vectoring capability such as a tilted rotor concept, it can be argued that the misalignment should be included in the propulsion system performance. On the other hand misalignment can also be included to accommodate the above mentioned concepts more appropriately. Both options will be presented here, the measure that does not include the full misalignment will still include the misalignment for installation effects of the propulsion system. The installed rational efficiency leaving the misalignment aside is

$$\Psi_{\text{syst.,inst. excl. misalign.}} = \frac{\begin{bmatrix} \mathrm{P}_{\text{T,prop. unit}} \\ -\mathrm{P}_{\text{T,prop. syst.-D incl. misalign.}} \\ -\mathrm{P}_{\text{T,prop. syst.-W incl. misalign.}} \end{bmatrix} + \left[(\dot{m}\varepsilon)_{\text{bleed}} + \mathrm{P}_{\text{s}}\right]_{\text{cabin}}}{\begin{bmatrix} \dot{m}_{\text{fuel}}\varepsilon_{\text{fuel}} \\ -\mathrm{P}_{\text{T,prop. syst.-D stored pot.}} \\ +\mathrm{P}_{\text{T,prop. syst.-D harvested pot.}} \end{bmatrix}}. \tag{2.51}$$

If one instead would include the misalignment into performance of the propulsion system it would lead to the following expression for the installed rational efficiency, it is

$$\Psi_{\text{syst.,inst. incl. misalign.}} = \frac{\begin{bmatrix} \mathrm{P}_{\text{T,prop. unit}} \\ -\mathrm{P}_{\text{T,prop. syst.-D excl. misalign.}} \\ -\mathrm{P}_{\text{T,prop. syst.-W excl. misalign.}} \\ -\mathrm{P}_{\text{T,misalign.}} \end{bmatrix} + \left[(\dot{m}\varepsilon)_{\text{bleed}} + \mathrm{P}_{\text{s}}\right]_{\text{cabin}}}{\begin{bmatrix} \dot{m}_{\text{fuel}}\varepsilon_{\text{fuel}} \\ -\mathrm{P}_{\text{T,prop. syst.-D stored pot.}} \\ +\mathrm{P}_{\text{T,prop. syst.-D harvested pot.}} \end{bmatrix}}. \tag{2.52}$$

This equations considers the control volume of the propulsion subsystem. It reflects upon the energy that is being stored as potential exergy as not consumed at that time instance but rather when it is being harvested and leaves the control volume.

2.4.3 Mission Assessment

The rational efficiency found in Eq.2.5 or the proposed installed rational efficiency detailed in Eq.2.51 and Eq.2.52 can also be used for mission assessments of the performance of the propulsion unit or propulsion subsystem, respectively. All these equations yields the efficiency as a fraction of two quantities on a power unit basis at a specific time instance. If the performance is evaluated over a time frame, such as a full aircraft mission, the assessment has to be on a work unit basis, i.e. power unit integrated over time. The mission rational efficiency becomes:

$$\Psi_{\text{mission}} = \frac{\int\limits_t \left(\mathrm{P}_{\mathrm{T}\text{prop. unit}} + [(\dot{m}\varepsilon)_{\text{bleed}} + \mathrm{P}_{\mathrm{s}}]_{\text{cabin}}\right) dt}{\int\limits_t \left(\dot{m}_{\text{fuel}}\varepsilon_{\text{fuel}}\right) dt} \tag{2.53}$$

The installed mission rational efficiency formulations are detailed in Eq.2.54 and Eq.2.55. The first formulation regards the misalignment of the thrust and the flight trajectory as outside the performance of the propulsion subsystem while the second formulation includes it.

$$\Psi_{\text{mission}-\text{syst,inst excl. misalign.}} = \frac{\int\limits_t \left(\begin{bmatrix} \mathrm{P}_{\text{T,prop. unit}} \\ -\mathrm{P}_{\text{T,prop. syst.-D incl. misalign.}} \\ -\mathrm{P}_{\text{T,prop. syst.-W incl. misalign.}} \end{bmatrix} + [(\dot{m}\varepsilon)_{\text{bleed}} + \mathrm{P}_{\mathrm{s}}]_{\text{cabin}}\right) dt}{\int\limits_t \left(\begin{bmatrix} \dot{m}_{\text{fuel}}\varepsilon_{\text{fuel}} \\ -\mathrm{P}_{\text{T,prop. syst.-D stored pot.}} \\ +\mathrm{P}_{\text{T,prop. syst.-D harvested pot.}} \end{bmatrix}\right) dt} \tag{2.54}$$

$$\Psi_{\text{mission}-\text{syst,inst incl. misalign.}} = \frac{\int\limits_t \left(\begin{bmatrix} \mathrm{P}_{\text{T,prop. unit}} \\ -\mathrm{P}_{\text{T,prop. syst.-D excl. misalign.}} \\ -\mathrm{P}_{\text{T,prop. syst.-W excl. misalign.}} \\ -\mathrm{P}_{\text{T,misalign.}} \end{bmatrix} + [(\dot{m}\varepsilon)_{\text{bleed}} + \mathrm{P}_{\mathrm{s}}]_{\text{cabin}}\right) dt}{\int\limits_t \left(\begin{bmatrix} \dot{m}_{\text{fuel}}\varepsilon_{\text{fuel}} \\ -\mathrm{P}_{\text{T,prop. syst.-D harvested pot.}} \\ +\mathrm{P}_{\text{T,prop. syst.-D harvested pot.}} \end{bmatrix}\right) dt} \tag{2.55}$$

Reference environment

Exergy is a property quantified as the work potential between the current state and an equilibrium state. For a propulsion unit the surroundings will be the ambient conditions and as previously described the ambient conditions stretches far enough that the gas flow in the aero engine will not change the ambient conditions. The ambient conditions will change drastically over an aircraft mission in terms of temperature and pressure. Rosen studied the impact of the choice of reference environment during a mission and concluded that having the reference environment constant, rather than changing with the mission, will lead to significant errors in the exergy analysis [21]. A reference environment other than the current ambient condition will lead to that the incoming air contains a magnitude of exergy different from zero. This incoming exergy cannot be used for the propulsion unit and will cause either a loss or a gain in the exhaust of the propulsion unit that has nothing to do with the true performance. A reference environment that varies in line with the mission points of the aircraft mission will lead to a true assessment of the propulsion system work and irreversibilities.

3 An Exergy Assessment of Modern Aero Engines and the Way Forward

This chapter assesses a modern turbofan, chosen for its dominating market share in modern commercial aviation. The analysis is made from an exergy perspective to illustrate the major loss sources. The drivers of the major loss sources are detailed and finally, an elaboration is made to detail innovative technology that can address these losses.

3.1 State of the Art Aero Engines

A modern direct-drive two-spool turbofan corresponding to a technology matureness of year 2020 was studied by the author in 2015 [7]. This analysis included the main points that constitutes a mission, i.e. take-off, mid climb, top of climb, begin of cruise, end of cruise and descent. A mission assessment was made by summing the mission point contributions with the corresponding duration of the mission that in whole can be classified as a short range mission for single-aisle aircraft. Based on this analysis a total mission exergy breakdown was made that included an installed subsystem perspective of what is useful for the aircraft, what needs to be compensated for in terms of added weight and drag from the engine and what was lost in the engine, see Fig.3.1. The engine losses were further detailed to assess the thermodynamic component contribution to the engine irreversibilities which is illustrated in Fig.3.2.

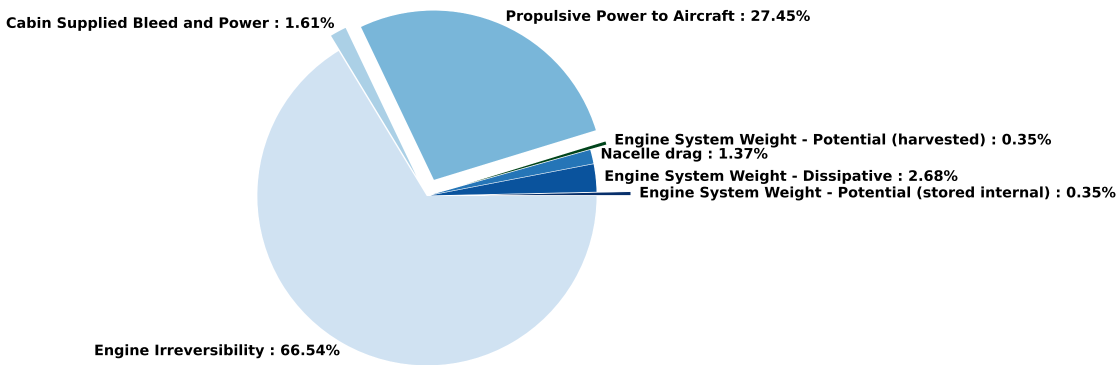

Figure 3.1: *A short mission total exergy breakdown for a modern turbofan (Thulin et al. 2015 [7]).*

The useful power generated by the propulsion system is the thrust it provides to the aircraft, the bleed and power it potentially supplies to the cabin and finally the potential energy that can be harvested in descent. The propulsive force generated by the turbofan amounted to 27.45 % of the total work potential in the fuel. The cabin supplied bleed and power is about seventeen times smaller. Parts of the energy it takes to lift the engine in climb is not dissipative, rather it is stored as potential energy that can be harvested during descent. The part of the exergy that transforms from fuel exergy to potential exergy is not considered as consumed before it is harvested in descent where it adds to useful power, as means for gliding. The dissipative part of the installation effects corresponds to almost one eight of the total propulsive force. Almost two thirds of the total work potential is lost in engine irreversibility, this is also more than sixteen times larger than the dissipative installation effects.

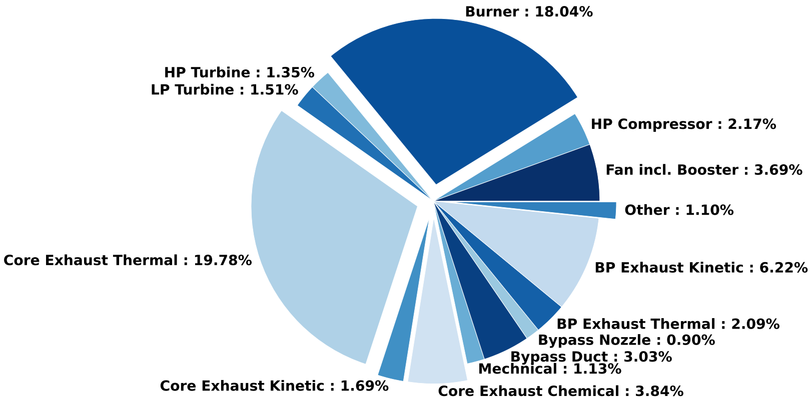

Figure 3.2: *A short mission total engine irreversibility breakdown of a modern turbofan (Thulin et al. 2015 [7]). When the irreversibility percentages are summed up they correspond to the engine irreversibilities divided by the provided fuel exergy as illustrated in Fig.3.1.*

The main loss sources in the turbofan can be found in the heat leaving the engine, the irreversibilities during combustion and the kinetic power that is not contributing to the propulsive force. These losses are further detailed below. It shall be noted that efficient turbomachinery and ducts are key for high system performance. In addition, since these parts are major weight drivers it is important that high efficiency is achieved at a low component weight. Turbomachinery that can achieve and resist high pressures and temperatures is also a key enabler for high cycle efficiency and to allow larger bypass ratios for higher propulsive efficiency. Moreover, well designed ducts are also important for the performance of the other components. More information about the various loss sources is included in the enclosed article from the 2015 ISABE conference [7].

3.1.1 Ejected Heat

A significant amount of work potential is lost for the system as hot gases leaves the core exhaust without producing thrust. This is a result of that flow is energized in the engine cycle and then not brought to equilibrium with its surroundings. The core nozzle exhaust gases for the simulated engine was in excess of 450 Kelvin warmer than the ambient temperature at cruise. Having higher thermal efficiency can help to limit the size of the core to reduce the ejected heat. The bypass flow also contribute to the ejected heat but is much lower since the enthalpy increase in the bypass flow only takes place in the fan, where the specific enthalpy increase is very limited in comparison to the core.

3.1.2 Combustion

Constant pressure combustion, as used in turbofans, is a process under which a lot of entropy is generated regardless of that the process is almost ideal. At a combustion efficiency at 99.8% and a low pressure loss coefficient the combustion generates a substantial exergy loss. The burner irreversibility as a major loss source is rather an inherent effect of burning fuel as it generates a substantial amount of entropy. It would be beneficial to combust at a steeper curve in a temperature-entropy (TS) diagram, i.e. during an increased pressure. To add to the combustion irreversibilities, the chemical exergy in the exhaust corresponding to a different gas composition compared to the ambient conditions is practically impossible to harvest. Hence, it can be seen as an inherent effect of burning fuel.

3.1.3 Non-propulsive Kinetic Power

Energy flows out of the nozzles in form of kinetic power. Part of the kinetic power is beneficial for the thrust to propel the aircraft while another part is not. While the thrust, based on the momentum, is increasing linearly with an increased nozzle velocity the kinetic energy is increasing quadratically. A lower thrust per mass flow unit, i.e. specific thrust, corresponding to the velocity difference between the nozzle velocity and flight velocity, in combination with higher total mass flow lowers these irreversibilities while being able to achieve the required total thrust. As a matter of fact the when the specific thrust goes towards zero these irreversibilities also goes towards zero. This has been a key driver in commercial aviation when going from turbojets towards low bypass ratio turbofans and later to high bypass turbofans as higher bypass ratios allow for a large mass flow in combination with a low specific thrust. The bypass nozzle flow with its much larger mass flow is the dominating contributor to this loss source.

3.2 The Way Forward

Radical technologies that can be utilized to address the major loss sources previously detailed are now presented. Innovations attacking the lost thermal power, i.e. when the hot gases leave the core nozzle, are initially presented. Ways to tackle the major entropy generation during combustion are thereafter elaborated upon. Configurations for achieving higher propulsive efficiency are then finally featured.

3.2.1 Ejected Heat

Recuperation, i.e. preheating the compressed gases before combustion by heat exchanging from the hot exhaust gases, can recover some of the thermal energy leaving the engine without producing any thrust. This will also lead to less fuel needed to reach the same combustion temperature and hence less entropy generation from combustion. The use of recuperation has been considered ranging back to the 1940s [22].

Intercooled cycles cool the gas between the intermediate and high pressure compressor by heat exchanging to the bypass air. Zhao et al. studied an intercooled turbofan in 2016 using exergy [6] and indicated a 5.3% fuel reduction when utilizing intercooling and redesigning the studied geared turbofan. Intercooling allows for less work input per unit compression in the high pressure compressor as it requires less energy to compress a cooler gas. Intercooling is also an enabler for higher pressure ratios as the corresponding high pressure compressor exit temperature decreases to be within the limits of what the material can withstand. This can be used to limit the core exhaust temperature and hence to reduce the thermal energy in hot gases that is ejected from nozzle.

A rather well-known innovative concept utilizing the synergy that intercooling and recuperation can offer. The concept, the IRA engine, was presented by Boggia and Rüd 2004 [23]. By intercooling the temperature difference in the recuperation will increase and thus enable a larger heat transfer with lower losses per unit of heat transfer. Intercooling in combination with recuperating for turbofans had been considered since the 1970s but indicated no real benefit [24, 25, 26] at that time as the technology was not mature enough. A geared turbofan equipped with intercooling in combination with recuperation was assessed using exergy by Grönstedt et al. in 2014 [5] and yielded a 4.2% fuel burn reduction compared to the reference turbofan corresponding to a technology level at year 2050.

Other technologies that have been discussed to recover some of the thermal energy leaving the engine has been to employ a secondary Rankine cycle and to use inter-turbine reheating. A turbofan in combination with a secondary Rankine cycle for flight applications was analyzed by Perullo et al. in 2013 [27]. Stationary gas turbines using secondary Rankine cycles have been successful to reach unrivalled efficiency. Inter-turbine reheat by combustion between the first and a second turbine can allow for higher specific power density [28] for a maximum allowed turbine inlet temperature. This can help to lower the size of the core to reduce ejected heat as well as to support ultra high bypass ratios.

3.2.2 Combustion

Piston engines was the predominant choice for powering aircraft until the mid-1950s. Already at this stage they featured pressures and temperatures unmatched by modern turbofans to yield specific fuel consumptions that match the most modern turbofan. Turbofans on the other hand offer a power to weight ratio that is outstanding, an extreme reliability as well as an inherently better ability to adopt to different ambient conditions as it does not suffer from a fixed stroke length. A composite engine cycle utilizing the possibility to achieve extremely high pressures and temperatures in a piston engine, as the peak conditions only apply temporary in the cyclic motion, in combination with the Brayton cycle was analyzed by Kaiser et al. in in 2015 [29]. The idea was building upon a geared two-spool turbofan configuration. The concept outlined the idea to continue compressing the core mass flow coming from the intermediate pressure compressor by first utilizing a turbocharger succeeded by piston compressors. The compressed air is thereafter mixed with fuel and ignited in piston engines under an initial isochoric combustion process which is continued by an isobaric combustion phase. The maximum peak pressure is corresponding to an overall pressure ratio at 300 in top of climb. After this the piston engine expands the air down to a pressure that corresponds to a temperature that can be handled after the Brayton combustion. Since a part of the combustion takes place during isochoric conditions this will correspond to a steeper curve in the temperature-entropy (TS) which implies less entropy generation. The cycle will also increase in thermal efficiency as the pressure ratio increases which in turn will enable a smaller core that can reduce ejected heat under the assumption that the hot gases leaves the engine at the same temperature. Initial studies indicated a fuel burn reduction of 15.2% compared to the reference geared turbofan corresponding to technology matureness at year 2025.

An alternative to achieve an intermediate combustion cycle is the relatively new innovation provided by the nutating disc concept that was presented by Meitner et al. in 2006 [30]. The concept is achieving a constant volume for combustion by having a round plate enclosed in a combustion chamber, placed central to the axis of rotation and leaned from the perpendicular direction of the shaft to create a nutating motion (wobbling). The concept has the advantage of offering a structurally balanced constant volume combustion, as the mass center always coincides with the rotation axis, and to be relatively light. It has already been tested for unmanned aerial vehicles in hope to provide low vibrations, high efficiency and compact installation. This concept could be used similar to the piston engine topping of the Brayton cycle mentioned above.

A third alternative to achieve constant volume combustion that is not dependent on being combined with a conventional Brayton combustor to reach high temperatures is the pulse detonation combustion concept. In a conventional combustor the combustion travels at ideally the subsonic flame temperature. If a detonation instead takes place it will propagate supersonically through shock waves so that the gas does not have the time to expand. A concept that is relying on pulse detonation in combination with an intercooled and recuperated cycle and that promise to recover some of the dynamics generated during the detonation waves was assessed using the exergy by Grönstedt et al. in 2014 [5]. Stators at the outlet of the pulse detonation chambers turn the flow to allow for extraction of sonic wave kinetic energy in the following rotor stage. A fuel burn reduction was estimated to 18.8% in cruise compared to a reference turbofan corresponding to a technology level at year 2050. The irreversibilities comparing an intercooled and recuperated cycle to one with the difference of additional pulse detonation combustion went from 19.5% to 16.9% of the total irreversibilities for the respective configuration.

3.2.3 Non-propulsive Kinetic Power

It is possible to lower the irreversibilities related to kinetic energy leaving the engine without producing thrust by lowering the specific thrust and consequently the fan pressure ratio. To reach the same thrust requirement it is needed to increase the mass flow. Open rotor and advanced geared ultra high bypass ratio turbofans allow for lower propulsive irreversibilities by enabling low specific thrust. Open rotor configurations rely on dual unducted counter-rotating rotors to replace the fan compared to a turbofan and can be designed to reach very high corresponding bypass ratios. A core of high power density, leading to a high overall pressure ratio, is key to enable powering the open rotor respectively the large fan blades.

4 Concluding remarks

A exergy framework has been developed to be used in state of the art engine performance codes to assess the component contribution to the overall system performance. The author was contributing to the first exergy studies on innovative engine concepts [5]. The investigated concepts included a turbofan reference corresponding to technology level at year 2050, an intercooled and recuperated engine, a pulse detonation combustion engine and an open rotor engine. The author did also participate in a study on intercooling in turbofan aero engines to enable better understanding of the benefits of the concept [6].

The developed exergy framework was also applied to the first mission study of a modern turbofan that corresponds to a typical airline operation [7]. This analysis also presented the *installed rational efficiency* concept, a true measure of the propulsion system performance, by compensating for the weight and drag associated with the engine to assess the useful power to the aircraft. The installation effects were also studied throughout the envelope of the mission to finally yield a mission total installed rational efficiency.

Using the developed framework to assess any type of propulsion system will be beneficial for improved understanding of the component losses in the system. In conjunction with conventional performance analysis methods this can then help exploring new innovative aero engine concepts in search for lower fuel consumption and thus lower emissions.

Bibliography

[1] J. M. Clarke and J. H. Horlock, "Availability and propulsion," *Journal of Mechanical Engineering Science*, vol. 17, p. 223, 1975.

[2] R. B. Evans, *A proof that essergy is the only consistent measure of potential work.* PhD thesis, Dartmouth College, 1969.

[3] H. M. Brilliant, "Second law analysis of present and future turbine engines," in *Joint Propulsion Conference*, 1995. AIAA 95-3030.

[4] B. Roth, R. McDonald, and D. Mavris, "A method for thermodynamic work potential analysis of aircraft engines," in *Joint Propulsion Conference*, vol. 38, July 2000. AIAA2002-3768.

[5] T. Grönstedt, M. Irannezhad, L. Xu, O. Thulin, and A. Lundbladh, "First and second law analysis of future aircraft engines," *Journal of Engineering For Gas Turbines and Power*, vol. 136, 2014.

[6] X. Zhao, O. Thulin, and T. Grönstedt, "First and second law analysis of intercooled turbofan engine," *Journal of Engineering For Gas Turbines and Power*, 2015.

[7] O. Thulin, T. Grönstedt, and J.-M. Rogero, "A mission assessment of aero engine losses," in *ISABE-2015-20121*, 2015.

[8] A. Arntz, O. Atinault, and A. Merlen, "Exergy-based formulation for aircraft aero-propulsive performance assessment: Theoretical development," *AIAA Journal*, vol. 53, pp. 1627–1639, 2016/03/22 2014.

[9] A. Arntz and D. Hue, "Exergy-based performance assessment of the nasa common research model," *AIAA Journal*, vol. 54, pp. 88–100, 2016/03/22 2015.

[10] T. J. Kotas, *The Exergy Method of Thermal Plant Analysis.* Butterworths, 1985.

[11] O. Reynolds, "Papers on mechanical and physical subjects," in *The Sub-Mechanics of the Universe*, vol. 3, Cambridge University Press, 1903.

[12] R. Clausius, "Über verschiedene für die Anwendung bequeme Formen der Hauptgleigungen der mechanische Wärmetheorie," *Annalen der Physik*, vol. 125, pp. 353–400, 1865.

[13] I. Dincer and M. A. Rosen, *Exergy, Energy, Environment and Sustainable Development.* Elsevier, 2007.

[14] Y. RAO, *Chemical Engineering Thermodynamics.* Orient BlackSwan, 1997.

[15] B. J. McBride and S. Gordon, *Computer Program for Calculation of Complex Equilibrium Compositions and Applications*, 1994. NASA RP-1311.

[16] Chevron U.S.A. Inc., *Aviation Fuels - Technical Review*, 2007. Available at `https://www.cgabusinessdesk.com/document/aviation_tech_review.pdf`.

[17] B. Roth and D. Mavris, *A generalized model for vehicle thermodynamic loss management and technology concept evaluation.* American Institute of Aeronautics and Astronautics, 2016/03/22 2000.

[18] B. Roth, *Aerodynamic drag loss chargeability and its implications in the vehicle design process.* American Institute of Aeronautics and Astronautics, 2001.

[19] B. Roth and D. Mavris, "Technology evaluation via loss managment models formulated in terms of vehicle weight," 2000. SAWE-2000-3001.

[20] D. M. J. Paulus and R. A. Gaggioli, "The exergy of lift and aircraft exergy flow diagrams," *International Journal of Thermodynamics*, vol. 6, pp. 149–156, 2003.

[21] M. A. Rosen, "Exergy losses for aerospace engines: effect of reference environment on assessment accuracy," *Exergy, an International Journal*, vol. 6, 2009.

[22] "Notes on the bristol theseus heat-exchanger propeller turbine," *Aircraft Engineering and Aerospace Technology*, vol. 18, no. 11, pp. 366–371, 1965.

[23] K. R. Stefano Boggia, "Intercooled and recuperated aero engine," 2004. AIAA 2005-4192.

[24] J. D. Eisenberg, *A preliminary study of the use of intercooling and reheat in conjunction with regeneration for aircraft turbine engines*, 1977.

[25] J. Kentfield, "Regenerative turbofans: a comparison with non regenerative units," *Journal of Aircraft*, vol. March, pp. 174–182, 1975.

[26] D. Gray and J. Witherspoon, "Fuel conservation propulsion concepts for future air transports," *SAE paper number 760535*, 1975.

[27] C. Perullo, D. N. Mavris, and E. Fonseca, "An integrated assessment of an organic rankine cycle concept for use in onboard aircraft power generation," *ASME Turbo Expo 2013: Turbine Technical Conference and Exposition.*

[28] N. Yannakoulis, "Introducing inter-turbine reheat in a high-bypass civil turbofan engine," Master's thesis, Cranfield University.

[29] S. Kaiser, S. Donnerhack, A. Lundbladh, and A. Seitz, *A Composite Cycle Engine Concept with Hecto-Pressure Ratio.* American Institute of Aeronautics and Astronautics, 2016/04/17 2015.

[30] G. Smith, P. Meitner, J. Jerovsek, and M. Boruta, *Meyer Nutating Disc Engine: A New Concept in Internal Combustion Engine Technology.* American Institute of Aeronautics and Astronautics, 2016/04/18 2007.