Design and Simulation of Performance of a Gas Turbine Compressor Running on Coal Syngas

Liz Wangui M., Dr. Eng. H. Ndiritu, Dr. B. Gathitu

Abstract

There is an increase in demand for electricity. Kenya relies heavily on hydropower as the main source of electricity. The cost of electricity in Kenya is high, it is 15 US cents per kWh as compared to South Africa which is 4 US cents per kWh. The frequency of power outages in Kenya is 33% compared to China which is 1%. Kenya imported 158 million kWh of electricity from Uganda and Tanzania in 2014. With the unveiling of laptop project for primary schools that is currently going on in Kenya, rural areas that did not have access to electricity will be connected to the national grid. This will increase the demand for electricity. In order to achieve vision 2030, more power has to be generated and at a lower cost. The electricity has to be from clean energy or renewable energy sources to reduce carbon emissions to the environment.

The government has invested in geothermal energy for power generation and this has reduced the use of gas turbines that run on fossil fuels. As of 2014, 558 MW of geothermal power had been installed. Renewable energy such as micro wind turbines, solar PV and solar water heaters are being used domestically to reduce the cost of electricity. The installation costs for these sources of renewable energy are costly and there are no proper ways of disposing them once they breakdown or they reach their life limit.

In this research a compressor will be designed and its performance simulated so as to study its effectiveness in generation of power from a syngas turbine. Syngas is obtained when organic wastes or coal is burnt in limited supply of oxygen. The design will entail blade sizing and profile development for the purpose of optimizing pressure ratio and efficiency. The performance will be simulated and optimized in ANSYS Fluent based on flow and geometric conditions. Simulation will involve solving the transport equations of flow and energy based on suitable modelling techniques to study what happens within the designed compressor.

It is expected that an optimized gas turbine compressor will be developed, and inlet conditions of pressure and flowrate will influence compressor efficiency and performance. The simulation results are expected to give an insight to designers of gas turbine devices used for power generation.

Keywords ANSYS (American Computer-aided Engineering Software) Fluent, Syngas, TPM (Tiny Particulate Matter), PM (Particulate Matter)

Liz Wangui, Department of Mechanical Engineering Jomo Kenyatta University of Agriculture and Technology P.O.BOX 6200-00200 Nairobi, Kenya. E-mail: lizmaina78@gmail.com

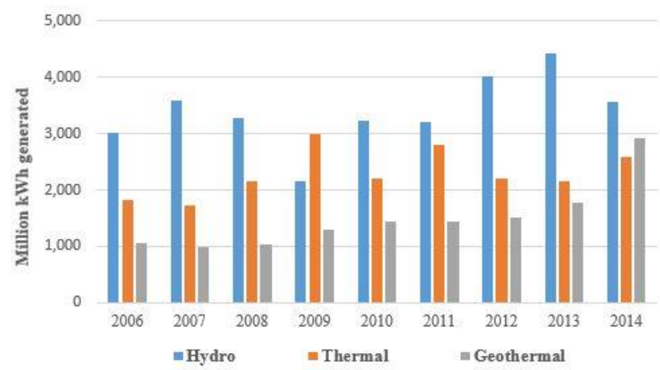
Eng. Dr. Hiram Ndiritu, Department of Mechanical Engineering, JKUAT, e-mail: hndiritu@eng.jkuat.ac.ke

Dr. Benson Gathitu, JKUAT, phone: +254723118800 email: bbg@eng.jkuat.ac.ke

I. Introduction

A. Background

Energy demand has grown rapidly because of countries developing and the improvement of living standards. Electricity is the world's fastest-growing form of end-use energy consumption (1). Due to this demand, electricity production has also risen by 76% for the past 20 years (2). Most gas turbines that generate electricity run on fossil fuels such as kerosene and natural gas. The prices of these fossil fuels are volatile since they are determined by players in the country of origin thus the cost of electricity generated is high (2). High prices of natural gas and emission concerns about natural gases has led to a focus shift in replacing these gases with gas derived from coal to run gas turbines (3). Kenya still relies on hydropower as the main source of electricity generation (4). The fluctuation of the hydro power is due to fluctuating river flow (Tana River which is the source of the 7-Folk dam), extreme evaporation rates, and sedimentation and siltation in the dams (5). The graph below shows hydro as the highest source of electricity generated in Kenya.



The government has tried to shift focus from hydropower through exploitation of geothermal energy and setting up of wind power plants. Off grid solar, micro hydro and other renewable energy systems are also being exploited.

A promising direction in coal conversion is coal gasification. With the discovery and subsequent mining of coal from Mui basin in Kenya, it is expected that electricity will soon be generated from coal. This supply can be used to boost the electricity generation that is currently being used.

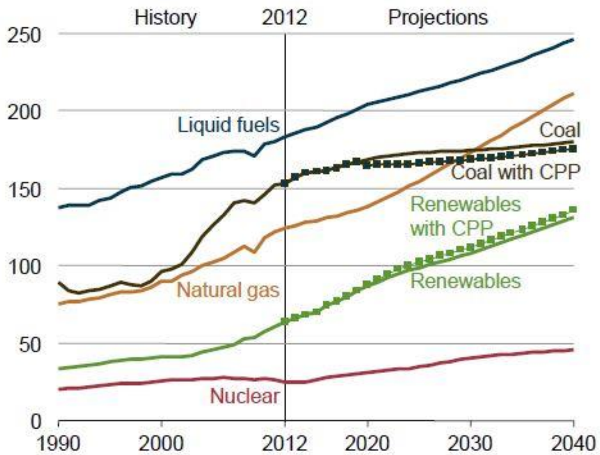
B. Syngas Utilization in Power Generation

The use of syngas energy is a new way to generate clean energy. Syngas fuels are obtained from coal, biomass or solid waste gasification processes. Gasification involves burning materials that have carbon in limited supply of oxygen (6). Gas turbine systems are more compact than internal combustion engines, their mechanical efficiency is higher, and they can be started and stopped more quickly than internal combustion engines (7).

C. Problem Statement

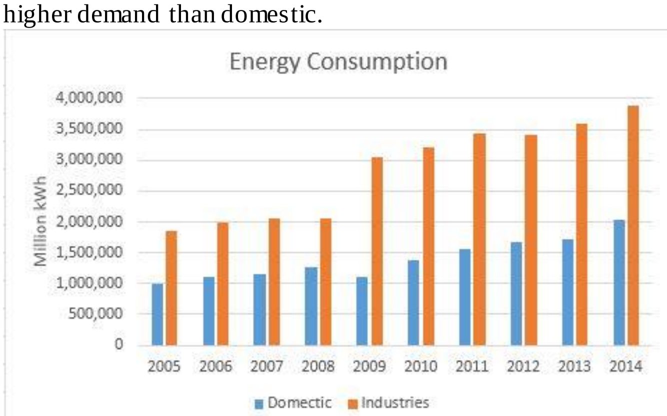
The energy demand has been on the rise due to economic development of countries, improved living standards, and industrialization. Figure below shows the annual rise in demand for energy with the most consumed being petroleum (1).

Figure ES-2. Total world energy consumption by energy source, 1990–2040 (quadrillion Btu)



Note: Dotted lines for coal and renewables show projected effects of the U.S. Clean Power Plan.

In Kenya, the need for energy has been on the increase for the past years. Due to over-reliance on hydroelectricity, the frequency of power outages is high (33% compared with the average for Mexico, China and South Africa, which stands at 1%). Production lost due to these outages is approximately 9.3% (compared with the average for Mexico, China and South Africa, which stands at 1.8 per cent). It takes approximately 66 days to obtain electricity connection in Kenya (compared with an average of 18 days in Mexico, China and South Africa (4).
The graph below shows the growing demand for energy from both domestic and industries, with industries recording the higher demand than domestic.



In Kenya, the rate of electricity is still high. The energy cost is 15 US cents per kWh while in South Africa it is 4 US cents per kWh. In China, it is 7 US cents per kWh while in Mexico it is 7.5 US cents per kWh. One of the goals of vision 2030 is to provide a utility sector (water, sewerage and electricity) that is modern, customer oriented and technologically-enabled to provide efficient, cost-effective, quality services to all citizens (8). This can only be achieved by ensuring that electricity production is efficient and affordable, and the source of energy is easily obtained.
The emission of carbon dioxide from existing coal based power plants is however considered one of the main factors responsible for climate change, commonly referred as greenhouse effect (9). Carbon dioxide, Sulphur and TPM produced while burning coal has led to build up of smog, haze, and acid rain in China.

D. Objectives

The main objective is to develop and simulate performance of syngas compressor for running a gas power plant. This will be done using ANSYS Fluent. The specific objectives are development of a model compressor that would operate on syngas. The performance of the compressor will be simulated using ANSYS to test influence of mass flow rate, inlet temperature, and pressure ratio. Finally, the compressor will be fabricated and resized for testing.

E. Justification

The use of coal in its raw form causes both health and environmental degradation. The conversion of coal to syngas is a clean way of utilizing the energy content of coal. This syngas can be compressed and fed into a turbine for power generation. Therefore, as the need for clean and renewable energy increases, coal gasification in power generation is the way to go. Also, with the discovery of coal in Kenya, this coal can be gasified and used in power generation.

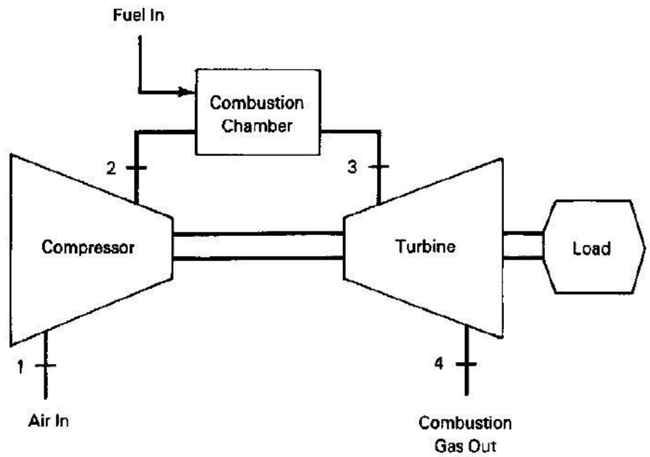
II. Literature

A. Overview

As the demand for energy increases globally and locally, more electricity has to be generated. Use of coal in its raw form is hazardous environmentally and health wise as well. Therefore, conversion of coal to syngas is a clean way of utilizing coal. This syngas can be fed to a gas turbine connected to a generator and used in the production of electricity.
Most gas turbines use natural gas in power generation. When natural gas is replaced with syngas, the flowrate through the gas turbine increases due to its lower calorific value (10).

B. Gas Turbine Concept

Gas turbines are used in airplanes, and in power generation (7). A simple gas turbine comprises of three elements; a compressor, combustor, and a turbine. The compressor is used to increase the pressure of the operating fluid by compressing it. The fluid then moves to the combustor where it is ignited, and then to the turbine where it is expanded and released. In power generation, the turbine-compressor shaft is coupled to a generator to produce electricity (11). Figure below shows this concept.



Gas turbines can operate with either axial compressors or centrifugal compressors. Centrifugal compressors can attain higher pressure ratios at one stage than axial compressor (12). Banpurkar et al. (13) recommends use of centrifugal compressor where high speeds are required.

C. Choke, Stall, and Surge in Compressors

In centrifugal compressors as mass flow is reduced, the pressure rise increases up to a given point at which further reduction of mass flow leads more or less rapidly to more or less severe instabilities like surge and stall (14). In manual transmission vehicles with turbo-chargers, surging occurs during gear change when the throttle is closed thus the air in the system lacks an outlet. The pressure build-up at the outlet becomes more than the inlet pressure thus backflow occurs (15).

Stall occurs when the radial velocity of the gas entering the diffuser, or efficiency of the diffuser, are too low therefore the flow collapses into stall cells as it passes through the diffuser. Stall is more prevalent on low flow impellers and is likely to occur on high pressure low flow applications. It tends to onset as the flow approaches surge.

Choke occurs when the flow is greater than the designed flow resulting in high gas velocities and incidence angles at impeller entry. Operating the machine choke region is usually harmless mechanically, but incurs efficiency losses (16).

The effects of surge are exponential temperature increase, process instability, potential machine trip, process shutdown and machine damage. Surge can be minimized and avoided by use of anti-surge systems. These can either be valves that drain off some of the fluid or programmable units that operate independently. Choke, surge, and stall negatively affect the efficiency of the compressor. When the compressor is operated at high flow rates, chocking occurs. Surge originates in the diffuser and is caused by surface friction that brings about restriction of flow.

Bosman et al. (17) designed an impeller using CAD (Computer Aided Drawing) and used NUMECA AutoGrid to mesh. He used CFD to simulate fluid flow and to analyze the impeller, and mean-line analysis to predict the performance of the designed impeller. He achieved a pressure ratio of 5.34 and an impeller efficiency of 91.6% and found out that the blade shape of the impeller influences its aerodynamic and mechanical performance. He suggested an impeller design with back-sweep at the outlet to avoid choke, improve compressor surge margin and to improve efficiency.

Neshat et al. (18) investigated the effects of blade sweep and lean on the performance of compressor. He did this using numerical solutions and found that an impeller blade with back sweep is less affected by lean, has reduced stall margin, and chocking flow rate reduced by 1.5%. For a blade with forward sweep, the stall margin increases and chocking flow rate increases by 0.18%. He concluded that forward swept blades influence upstream flow while backward swept blades affect the rotor stages downstream.

Wang et al. (16) paper focused on the performance of backward swept impeller on the performance of the centrifugal compressor. During the investigation, a 3D model of the impeller was designed using Vista CCD in ANSYS Workbench and CFD analysis. The results were that backward swept impellers offer better isentropic efficiencies than radial impellers, and that they improve volume flow rate and enhance outlet velocity of the compressor.

D. Blade Configuration

In compressors, the most crucial element is the impeller. This is because the impeller transfers kinetic energy to the working fluid (13). Blades should be designed in a way that minimizes flow loses. Variables in the impellers that influence efficiency, operating range and blade stress in the compressor are: impeller tip diameter, back-sweep angle, tip/exit depth, inducer inlet angle and rotor eye, blade leading edge shape, curvature of blade shape and, tip clearance.

Blade lead increases the pressure on the pressure surface. Forward swept blades have a better performance and increase compressor efficiency by almost 1% while backward swept blades increase the efficiency by 0.5%. Forward swept blades reduce the interaction between the shockwave and the casing wall boundary layer while the backward swept blades reduce chocking flow rate. Therefore both sweep and lean should be present in a blade design since they improve chocking flow rate and efficiency in various operating ranges of a compressor (18).

E. Diffuser Influence

Diffusers are located downstream of the impellers in centrifugal compressors. There are vaned and vaneless diffusers.

The diffusers affect the static pressure at the outlet of the compressor. Stall may develop into a surge at diffuser outlet thus it is important to determine what type and design of a diffuser is required (19). Taher et al. (19) aim at conducting his investigation was to compare flow and behavior characteristics near surge conditions in vaneless and vaned diffusers. He used numerical simulations and found that at near surge conditions, static pressure fluctuations at the inlet of the diffusers was higher in vaneless diffusers than in vaned diffusers. He also found out that pressure drop during surge occurs faster in vaneless diffusers than in vaned diffusers. He concluded that compressors with vaneless diffusers are more stable during surge than those with vaned diffusers. In his research, he investigated pressure and velocity in vaned and vaneless diffusers. He did not look at how temperature would fluctuate and be affected by vaned and vaneless diffusers.

Sorokes and Kuzdal et al. (20) in their discussion of the evolution of centrifugal compressors noted that vaneless diffusers offer wider flow range than vaned diffusers. They also noted that static pressure recovery is higher in vaned diffusers than in vaneless diffusers.

F. Syngas in Gas Turbine Systems

Gasification is a process that converts low quality fuels to valuable ones. The process can be applied to biomass as well as coal. Gas generated by gasification of coal comprises of H_2 and CO and small amounts of CH_4 and higher order carbons. Impurities such as Sulphur, alkali species, and small particulate matter are also present but can be eliminated by employing a cleaning process of the syngas (3).

Suhui et al. (21) investigated the behavior of syngas in spark ignition using gas turbine start up conditions, and the effects of the syngas fuel composition and air flow on ignition performance. He discovered that syngas has better ignition performance as compared to natural gas though one of the hindrance of using syngas in gas turbine is its change in composition and heating value.

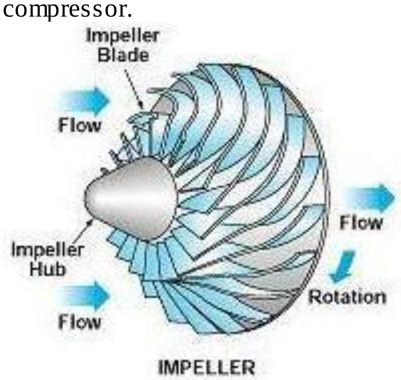
G. Gaps Identified in Literature

i. Surge, choke and stall affect flow of diffusers and there is need to reduce their impact on performance of diffusers.

III. Methodology

A. Domain Configuration

The passages within the compressor will be designed in 3-Dimensional plane using suitable criteria. For the curves of the impeller, and flow passages. Bezier curves will be formulated using design points. This will ensure that a smooth curve is designed. Figure below shows a design of a centrifugal compressor.



During the design phase, the compressor hub and shroud profiles will be developed based on appropriate design guidelines.

B. Governing Equations

Mass conservation equation

$$\nabla V_i = 0$$

Momentum conservation equation

$$\rho(\nabla V_i) = F_i - \nabla . P + \mu \nabla^2 V_i$$

Energy conservation equation

$$\nabla[(\nabla . \rho V_i)(C_p T) - \frac{\lambda}{C_p}\nabla . (C_p T_i)] = \dot{H}$$

Species conservation equation

$$\nabla(\rho V_i) = \nabla . (\rho D \nabla . Y) - \omega$$

These governing equations will be solved using finite volume method for steady-state flows, and RANS for turbulent flows.

C. Finite Volume Method

Many codes used to solve fluid flow problems use finite volume method. This is because it is convenient for use with unstructured grids, and for its global conservation property. This global conservation property is the principle of conservation produces over the entire domain. Some of the general purpose codes used for fluid ow are CFD programs. Solution of this method starts with the conservation laws in integral form. Finite volume solves the governing equations. These can be structured or unstructured grids (22). There are grid points within each cell. The principle of conservation is reproduced for the entire domain. An equation solved by finite volume method is:

$$\frac{d}{dt}\int_{\Omega} \Phi \, d\Omega = -\int_{s} \Phi V . ndS + \int_{s} X \nabla \Phi . ndS + \int_{\Omega} Q d\Omega$$

D. Reynold-Averaged Navier Stokes Equation

Reynold-Averaged Navier Stokes (RANS) equation remains as a primary tool of practical CFD analysis. It is simple, has a broad selection of models, and can be applied to different kinds of turbulent flows (22). The governing equation will be modelled using RANS method. The universally applicable ensemble-averaged field will be:

$$< u > (x,t) = lim_{m \to \infty} \frac{1}{M}\sum_{m=1}^{M} u^{(m)}(x,t)$$

, where $u^{(m)}$ are the realization of flow in M identical experiments.

Using Reynolds-Averaged equation and Newtonian equations, the Reynolds-Averaged Navier Stokes equation for an open system will be written as:

$$\rho \frac{\partial < u_i >}{dt} + \rho \frac{\partial}{\partial x_j}(< u_i >< u_j >) = -\frac{\partial < p >}{\partial x_i} + \mu \nabla^2 < u_i > - \frac{\partial \tau_{ij}}{\partial x_j}, \frac{\partial < u_i >}{\partial x_i}$$

In the two equation model, velocity and length will be determined. The two models to be used are $k - \epsilon$ model and $k - \omega$ model. The $k - \epsilon$ model will use transport equations for turbulent kinetic energy and the rate of viscous dissipation. The k-equation will be given as:

$$\rho \frac{\partial k}{\partial t} + \rho < u_j > \frac{\partial k}{\partial x_j} = 2\mu_t < S_{ij} > \frac{\partial u_i}{\partial x_j} - \rho\epsilon + \frac{\partial}{\partial x_j}[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}]$$

With boundary conditions set in place, the above equations will be used to solve near-wall treatment turbulent flows. These will be used at boundary walls. Inlet conditions into the compressor will also be solved using $k - \epsilon$ equation.

E. Recommendations

There exist literature on how surge, stall, and choke affect the compressor performance. Several gaps have been identified in the literature and these will be key areas that will be focused on during the study of centrifugal compressors. Some of these are:

i. Surge, choke and stall affect flow of diffusers and there is need to reduce their impact on performance of diffusers.
ii. It is essential to study the onset of surge in a backward swept impeller, and how the angle of sweep reduces or increases surge occurrence.
iii. How the configuration of diffusers affect the stability. It is therefore necessary to study the use of vaned and vaneless diffusers in a bid to minimize instability, their effects in the centrifugal compressor to determine which diffuser is suitable for which sweep.

IV. Expected Results

The centrifugal compressor running on syngas will be designed, and simulated using ANSYS Fluent CFD. Its geometry will be investigated to determine how it influences pressure, temperature, and velocity.

a. Design of a compressor for use in gas turbine running on syngas.
b. Simulation results of the performance of the compressor based on pressure, velocity field and temperature across the compressor.
c. Influence of transport properties on the surge, stall, and choke of the compressor
d. A fabricated centrifugal compressor that compressed syngas.

V. Conclusions

The need for energy globally and in Kenya requires more sources of energy to be utilized. The effects of pollution is now being felt thus those sources have to be clean. Coal from Mui Basin can be a source for power generation in Kenya.

Surge, stall, and choke are common problems that affect the performance of a compressor in a gas turbine running on syngas. Thus, their onset needs to be further studied. Also, the effects of the compressor profile on surge, stall, and choke need to be investigated further so that an optimized and efficient compressor can be used.

VI. Acknowledgement

I would like to thank my supervisors for their guidance during research, development of the proposal, and ongoing design and analysis. Also, the department of Mechanical Engineering and JKUAT for availing the websites at which research materials can be obtained.

References

[1] *International Energy Outlook.* May 2016.
[2] Council, W.E. *World Energy Resource Survey.* 2013.
[3] G.Wright, T. B. Gibbons and I. *A review of materials for gas turbines firing syngas fuels.* 2007.
[4] Statistics, Kenya National Bureau of. *Statistical Abstract.* 2015.
[5] *Vulnerability of hydro-electric energy resources in kenya due to climate change effects: The case of the seven folks project.* Bunyasi, M. M. 2012, Journal of Agriculture and Environmental Sciences, pp. 36-49.
[6] *Coal gasification integration with solid oxide fuel cell and chemical looping combustion for high-efficiency power generation with inherent CO2 Capture.* Lior, W. X. Shiyi Chen and Noam. 2015, Elsevier: Applied Energy, pp. 298-312.
[7] *Thermodynamic analysis of a gas turbine power plant modeled with an evaporative cooler.* Kilanko, S. O. Oyedepo and O. 2014, International Journal of Thermodynamics, pp. 14-20.
[8] *Kenya Vision 2030.*
[9] Rubanova, A. *History of Compressors.*
[10] *Performance maximization of IGCC plant considering operating limitations of a gas turbine and ambient temperature.* Do Won Kang, Chang Min Kim, Jae Hong Lee, Tong Seop Kim, and Jeong L. Sohn. s.l. : Journal of Mechanical Science and Technology, 2016, Vol. 30.
[11] P.Spittle. *Gas Turbine Technology.* s.l. : Rolls Royce, 2003.
[12] *A micro gt unit for electric power generation: Design and testing of turbine and compressor.* Varplaetsen, D. R. J. Peirs and F. 2004. 9th International conference on new actuators.
[13] 13. *Review paper on stress distribution over the blade of compresor of micro turbine.* R.D.Banpurkar, P. 2015, International Journal of Advanced Engineering and Global Technology.
[14] *Full-annulus simulation of the surge inception in a transonic centrifugal compressor.* Trbinjac, E. B. I. 2015, Journal of Thermal Science.
[15] http://ksmotorsport.co.za/flutter-compressor-surge/. *Turbo flutter/compressor surge.*
[16] *Back swept angle performance analysis of centrifugal compressor.* Wang, T. 2014, MECHANIKA, pp. 402-406.
[17] 17. Merwe, B. B. van der. *Design of a Centrifugal Compressor Impeller for Micro Gas Turbine Application.* 2012.
[18] 18. *Investigating the effect of blade sweep and lean in one stage of an industrial gas turbine's transonic compressor.* Neshat, M.A. 2015, Propulsion and Power Research, pp. 221-229.
[19] 19. *Numerical investigation of rotating stall in centrifugal compressor with vaned and vaneless diffuser.* Halawa, M. A. Taher. 2015, Journal of thermal science, pp. 323-333.
[20] *Centrifugal compressors evolution.* Sorokes, James M. 2010. Proceedings of the 39th Turbomachinery Symposium.
[21] *Syngas spark ignition behavior at simulated gas turbine startup conditions.* Li, S. 2014, Combustion Science and Technology, pp. 1005-1024.
[22] Zikanov, O. *Essential Computational Fluid Dynamics.* s.l. : John Wiley & Sons, Inc., 2010.