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1. Gas Turbine Power Augmentation by Multistage Injection of Treated Water into Compressor Stator Porous Blades

Gas turbine power augmentation can be achieved by different methods. Methods used today in power industry include:

- ***Compressor inlet air evaporative cooling (fogging technology)***
  This technology has the lowest capital investment, but its performance is heavily dependent upon ambient conditions (the minimum temperature to which inlet air can be cooled by evaporation of injected water spray is its wet bulb temperature). In practice, the maximum effect of power augmentation achieved by this method does not exceed 8.0% of the turbine nominal capacity.
- ***Compressor intercooling***. Today this method is applicable only to aero-derivative gas turbines which have a specially designed space gap between the low pressure section and high pressure section of compressor. Intercooling is performed by injecting atomized cooling water spray into this gap. Compressors of industrial gas turbines do not have such a space gap and, subsequently no inter-cooling can be used for industrial gas turbines.
- ***Compressor inlet air chilling*** is the most widely used technology for industrial gas turbine power augmentation. The air chilling system includes absorption or electrically driven mechanical chiller with cooling tower and auxiliary equipment. Chilling systems are more effective than the fogging technology or intercooling and can provide power augmentation effect of 16% -18% of nominal capacity, but chillers are very expensive. Their capital and O&M costs are the highest among competing technologies.

- **Proposed new technology: Power augmentation by multistage injection of saturated water into compressor stator porous blades**
  This concept is based on injection of pressurized saturated water into compressor stator blades at all stages of compression (except the first and the last stages). The surface of stator blades should be made porous so the saturated water passing through porous wall would sustain substantial pressure drop and as result flash into compressed air. The cooling effect will be measured by the latent heat of vaporization multiplied by the water injection rate.
  The expected power augmentation effect for gas turbine could exceed 20% and is limited only by design margins of electrical generator.

  The project goals:
  1. Estimation of the maximum air cooling effect produced by water evaporation at different compression stages and determination of an optimal number of water injection stages limited by about 20% power augmentation of gas turbine at nominal capacity. To achieve the required power augmentation we may not have to use all compressor stages for water injection.
  2. Optimal design of pressurized saturated water delivery and distribution system that provides the cooling effect by flashing through porous blades. This task will also include determination of number and diameter of pores (perforations) in the stator blades at each relevant compression stage.
  3. Cost estimation of the multistage injection system. Cost - Benefit analysis relative to other available power augmentation technologies.

***Items 2 and 3 should be performed for two options**:* **A**. Gas turbine operates in a simple cycle **B**. Gas turbine operates in combined cycle.

The project implementation steps:

1. Calculation of Pressure, temperature, work and relative humidity at the exit of each selected compression stage of the given axial compressor.
2. Calculation of maximum water vaporization rate that yields to 100% RH in the air at each selected compression stage. This will establish maximum theoretical cooling effect. After addition of vapor to air the overall volumetric flow must be recalculated. If the re-calculated overall volumetric flow exceeds the value corresponding to the standard case (no water injection), then water injection rate or air flow should be adjusted in such a way that total volumetric flow remains nearly the same.
3. Calculation of diameter and a number of pores (perforations) as well as associated pressure losses in the stator blades at each selected compression stage.
4. Hydraulic and mechanical design of multi-staged water injection system.
5. Cost - benefit analysis of the multi-staged air cooling system

Minimum requirements for student:

1. Good knowledge of thermodynamics, fluid mechanics and heat transfer.
2. Familiarity with basic performance analysis of gas turbines and compressors
3. Basic knowledge of cost - benefit analysis (engineering economics)

Full project implementation requires two students

One student will analyze option **A** and the other student - option **B**

2. Integration of Liquefied Air Energy Storage (LAES) with Gas Turbine Combined Cycle as a Tool for Cost-Effective Stabilization of Electrical System under Large Scale Renewable Energy Implementation.

Background:

Large scale introduction of renewable energy leads to changes in load profile of conventional power generation plants. Solar power plants operate at high load during mid-day hours with no power production during evening, night and morning hours. Consequently, electric system operators require conventional units to operate at peak load in the morning and evening hours and at low partial loads during mid-day and night hours. Some conventional units could operate with two start-ups and two shut downs a day.

The second problem is that large scale introduction of renewable energy (wind and solar) requires large amount of spinning reserve in the electric system due to generation instability of wind and solar power plants. The spinning reserve should be fast enough in response to change of demand for power. That requires fast load ramp-up and ramp-down of conventional power plants.

All this leads to significant increase of cost of operation and maintenance (O&M) from conventional power plants and reduces their reliability.

Peak shaving (a solution for the first problem) and rapid and cost-effective load response (a solution for the second problem) can be provided by liquefied air thermal energy storage (LAES).

Liquefied air thermal storage (LAES) unit consists of two sub-systems. The first (thermal energy storage – energy charging mode) sub-system produces liquid air during low demand hours (night and mid-day hours) of conventional power plants, and stores the liquid air in thermally insulated tank at cryogenic temperature. The second (thermal energy discharge - power production) sub-system pumps liquid air from the tank through a heater - heat exchanger that uses waste heat from the conventional power plant. The liquid air evaporates increasing its volume and enters the turbine-expander-generator set that provides electric power back to the grid during the hours of high power demand from the conventional plants.

LAES power charging during low demand hours and power discharge during the hours of high power demand prevents the conventional plants large-amplitude load changes and frequent shut downs. Very flexible power production provides required fast power reserve to the electric system and prevents the conventional plants from frequent and large load fluctuations.

<u>Proposed new technology</u>: Integration of liquefied air energy storage (LAES) with gas turbine combined cycle (GTCC)

Integration of large scale energy storage with existing or new gas turbine combined cycle (GTCC) plant provides a proper loading of GTCC without shut downs for the periods of low demand for power or excessive load modulation during the day time and evenings. During the period of low demand for power energy storage accumulates energy produced by GTCC and stores it until demand for electricity in the grid sharply rises. At that moment energy storage discharges power back to the grid in parallel with the GTCC.

Integration of Liquefied air thermal storage (LAES) and gas turbine combined cycle (GTCC) increase overall thermal and economic efficiency of power production, and could be accomplished in several ways: use of GTCC waste heat during LAES power production, use of stored cold surpluses for GTCC efficiency enhancement and power augmentation, etc.

The project goal:

Development of computational techno-economic model computing load, electricity cost and emissions from every power generation unit in the electric system which consists of GTCCs, solar and wind power plants and LAES facilities

Project implementation steps

1. Development of mass-flow-energy model of LAES unit with different level of its integration with GTCC.
2. Performing techno-economic study of integration of LAES and GTCC units in comparison with shifting operation of GTCC alone under different power production scale of solar and wind energy. The study will include GTCC response to solar and wind power fluctuations during day-evening-night-morning hours as well as fast solar and wind power fluctuations.
3. Optimization of LAES unit capacity and level of its integration with GTCC corresponding to degree of solar and wind power generation scale.

Full implementation of the project requires two students.
For a single student the project scope can be scaled down to optimization of LAES unit capacity at given integration with GTCC and given degree of solar and wind power generation scale.

Minimum requirements for students:

1. Good knowledge of thermodynamics and heat transfer.
2. Familiarity with conventional power plant principles of operation and performance of major equipment (turbines, compressors, steam generators and etc.)
3. Basic knowledge of cost - benefit analysis (engineering economics)
4. Basic programming capabilities using one of the following codes: FORTRAN, C, C++, Visual Basic, MATLAB

3. Development of GT combined cycle new start-up procedure which reduces fatigue damage of HRSG, fuel consumption and emissions of NOx and CO

Brief review of conventional start procedure of combined cycle

Conventional start procedure of combined cycle begins by gas turbine ventilation on crank rotation (about 500 rpm) during about 10 minutes. After the ventilation, fuel ignition is initiated in combustor(s) of gas turbine. At this moment a temperature of flue gases in gas turbine exhaust rises sharply from about 30ºC up to about 450ºC. During 3-5 minutes after the ignition, gas turbine rotation increases from crank speed (about 500rpm) to 3000 rpm – the synchronization speed. During these 3-5 minutes the exhaust temperature reduces by about 100ºC.

After gas turbine generator synchronization, gas turbine increases its output up to its minimum environmental load (the minimum load with low emissions, usually 40-50% of nominal load) by about 5-10 minutes. During this time the exhaust temperature increases from about 350ºC to about 500ºC. Gas turbine stays at this load until HRSG heats up and produces a stable steam flow through superheater and re-heater, and steam turbine reaches synchronization speed. At this moment (in the case of multi-shaft configuration when steam turbine has its own electrical generator), the steam turbine generator is also synchronized. In the case of single-shaft combined cycle configuration (gas turbine and steam turbine are connected to a single generator), steam turbine connects by automatic clutch to just synchronized generator. After this moment, both gas turbine and steam turbine raise their load up to their nominal load.

The gas turbine operation at minimum load (during HRSG and steam turbine heating up process) could take up to 90-100 minutes during a cold start, or 30-45 minutes during hot start.
This start procedure has two major drawbacks:

1. HRSG tubes suffer from sharp changes of inlet flue gas temperatures, which results in their thermal fatigue damage and, consequently, reduction of their life.
2. Prolonged stay of gas turbine on minimum load with extremely low efficiency results in high fuel consumption during combined cycle start-up procedure.

Proposed new technology:

Preliminary gradual heating-up of HRSG and steam turbine before the gas turbine ignition provides a significant reduction of the thermal fatigue damage during combined cycle start procedure.
Preliminary heating-up of HRSG shortens gas turbine start procedure, specifically operation on minimum load, and thus reduces fuel consumption during combined cycle start procedure.
The preliminary heating-up is provided by in-duct burners, which are installed upstream of HRSG and use the air flow provided by the gas turbine operating on crank speed.

The project implementation steps:

1. Survey of start-up procedures of single-shaft and multi-shaft combined cycles
2. Survey of thermal fatigue correlation to metal temperature fluctuations.
3. Development of flue gas turbine exhaust flow-temperature model for combined cycle start up.
4. Development of HRSG tube heat transfer model for combined cycle start up procedure using finite element method and performing subsequent thermal stress analysis.
5. Assessment of HRSG thermal fatigue damage during combined cycle start up
6. Comparative techno-economic analysis of the existing and proposed combined cycle start-ups
7. Development of conceptual design of the system for preliminary heating-up of HRSG.

Minimum requirements for graduate students:

1. Solid knowledge of thermodynamics and heat transfer.
2. Basic knowledge of thermal fatigue principles
3. Basic knowledge of cost - benefit analysis (engineering economics)

4. Gas turbine power augmentation and efficiency enhancement by increasing turbine inlet temperature preserving the design turbine blade temperature by intensified blade cooling.

Brief review of turbine blade cooling in gas turbine technology

It is obvious fact that use of higher turbine inlet temperature and pressure leads to higher gas turbine power output and higher efficiency. In modern industrial gas turbines this temperature is in the range 1500 C -1550 C. First-row turbine blades have about 850 C metal temperature, which is developed as result of heat transfer equilibrium between hot combustion gases flowing outside the blades and relatively cold cooling air flowing inside the blades. The cooling air, which is extracted from the air flow at compressor outlet, passes through turbine blade inner volume and exits to the combustion gases through multiple small holes in the blade walls. In gas turbines, a cooling air temperature depends on a temperature of air at compressor outlet. In modern gas turbine compressor having high compression ratio, the exit air temperature (and turbine blade cooling air) could reach 400-420 C.

The blade temperature could not be increased without severe reduction of blade life cycle and its reliability. Increasing of cooling air flow leads to reduction of gas turbine performance, which, in turn, could nullify a performance gain, expected as a result of turbine inlet temperature increase.

We see two main ways to increase the turbine inlet temperature without reduction of blade life cycle and reliability. The first way is focused on development of new more sophisticated blade materials, which could ensure blade operation at higher temperatures. The second way requires better blade cooling, which ensures the same blade metal temperature even at higher temperature of combustion gases.

The first way requires huge long-term R&D investments in the fields of materials and their processing. The second way could provide a short-term and low-cost solution under condition that the cooling air flow rate will not be increased. This could be achieved by the use of colder cooling air. The simplest and most cost effective solution for reducing cooling air temperature is evaporative air cooling by injecting tiny water droplets into pressurized air stream. At high pressure air is capable of absorbing large quantities of water vapors which may lead to drastic reduction of air temperature. This method can significantly enhance turbine blade cooling.

Proposed new technology: Turbine blades cooling enhancement by atomized water spray injection into hot air stream extracted from the compressor exit space and directed to gas turbine blades.

The project goal: Development of low cost auxiliary system that substantially enhances turbine blades cooling without increasing air extraction rate for cooling purposes.

Project implementation steps:

1. Development of thermodynamic model of turbine stage.
2. Development of heat transfer model of turbine stage.
3. Survey of water atomizing technologies and choosing the appropriate technology.
4. Investigation of effect of water fog evaporation in the cooling air on turbine blade temperature
5. Investigation of potential of gas turbine augmentation by reduction of required cooling air flow.
6. Investigation of potential of gas turbine augmentation by increasing of combustion gas temperature at the turbine inlet.
7. Comparative techno-economic analysis of the two cases of gas turbine augmentation.
8. Development of conceptual design of the system of water atomizing at compressor outlet (water treatment, storage, pumping and atomization)

Minimum requirements for graduate students:

1. Solid knowledge of thermodynamics, fluid dynamics and heat transfer.
3. Familiarity with basic operation principles of gas turbines
4. Basic knowledge of cost - benefit analysis (engineering economics)

5. Techno-Economic Evaluation of coal fired power plant having de-NOx system (SCR -Selective Catalytic Reactor) installed after flue gas clean-up facilities.

By existing environmental regulations exhaust gases emitted by power plants must be cleaned from harmful emissions such as sulfur oxides (SOx), nitrous oxides (NOx), CO and particles (fly ash). SCR system that removes NOx emissions from exhaust gas is located in the high temperature exhaust section upstream of other clean-up facilities. The reason for this design feature is the fact that maximum performance of SCR system occurs at high temperatures of exhaust gas.

At the same time, dirty exhaust gas that flows through the SCR plates made of porous catalytic material pollutes the catalyst and cause a drastic reduction in NOx capture effectiveness over time. This makes the maintenance of SCR much more expensive. The replacement cost of catalyst block (or plate) is tremendous, also a very frequent washing of catalyst contributes to a sharp rise in the maintenance cost. The goal of the proposed project is to find less expensive solution to the problem of SCR catalyst degradation caused by various impurities in the exhaust gas.

Proposed solution: If instead off keeping the SCR system in its current location at power plant we install it after FGD (Flue Gas de-Sulfurization), ESP (Electro-Static Precipitator) and bag filters, the SCR will process the cleaner exhaust gas free of fly ash, soot, sulfur oxides and other pollutants. In this case the degradation of SCR catalyst will be much slower than in the current situation.

However, the transfer of SCR from high temperature to low temperature section of exhaust line will force the de-NOx system to operate far from the optimal point of operation which is typically located in the temperature range of 300 - 350 C. To correct this problem, we need to heat up the exhaust gas to appropriate temperature and to achieve optimal operation of SCR on “clean” exhaust.
There are two alternative approaches that can resolve this problem, but both options will have a different impact on the efficiency and the cost of power plant retrofit.

First method: Heating up the exhaust gas before it enters the SCR using natural gas fired burner. This method has a relatively low capital investment but may reduce the efficiency of power plant and increase the temperature of exhaust gas entering the stack.
Second method*:* Exhaust gas will be compressed before entering the SCR in order to obtain optimal temperature for SCR operation. After SCR the exhaust gas will be expanded in turbo-expander producing additional work and cooled exhaust gas.
In the framework of this project we intend to investigate both methods of SCR cost reduction and to choose the most cost-effective one.

Minimum requirements for student:

1. Solid knowledge of thermodynamics, heat transfer and fluid mechanics.
2. Basic knowledge of coal-fired power plant
3. Familiarity with compressors and turbo-expanders
4. Basic knowledge of cost - benefit analysis (engineering economics)

6. שם הפרויקט: תכנון ובחינה טכנו-כלכלית של מתקן אגירת אנרגיה תרמית המבוסס על ניזול אוויר קריאוגני

רקע

כללי תפעול המערכת ליצור חשמל דורשים תגובה מהירה בייצור חשמל בהתאם לשינוים בצריכת חשמל. באופן כללי תחנות הכוח יכולות לספק תגובה כזאת תמורת הקטנת אורך חייהם, הגדלת זיהום אוויר וצריכה נוספת בדלק. זה פיטרון מאוד יקר ויש אפשרות למצוא חלופה יותר טובה מבחינה כלכלית. אחד מחלופת האלו זה שימוש במערכת אגירה ופריקת האנרגיה המבוססת על ניזול של אוור דחוס.

מטרת הפרויקט

לתכנן מערכת אגירה ופריקת אנרגיה ולבצע אנליזה תכנו-כלכלית.
על סמך הנתונים ודרישות למערכת אגירת אנרגיה יש לתכנן מערך מדחסי אויר עם קירור ביניים, מחליפי חום, מערכת החסון של אויר נוזלי, טורבו-גנרטורים ליצר חשמל ומגדלי תעינה ופריקת חום עם ניזול אויר.
במערכת אגירת חום של 300 MW יש צורך לתכנן מגדלי אגירה ופריקת חום שמכילים בתוכם חומר מינרלי בצורת אבנים קטנים שסופגים חום או קור מאויר שעובר דרכם (Thermal Design of Packed Bed).

עקרונות פעולה

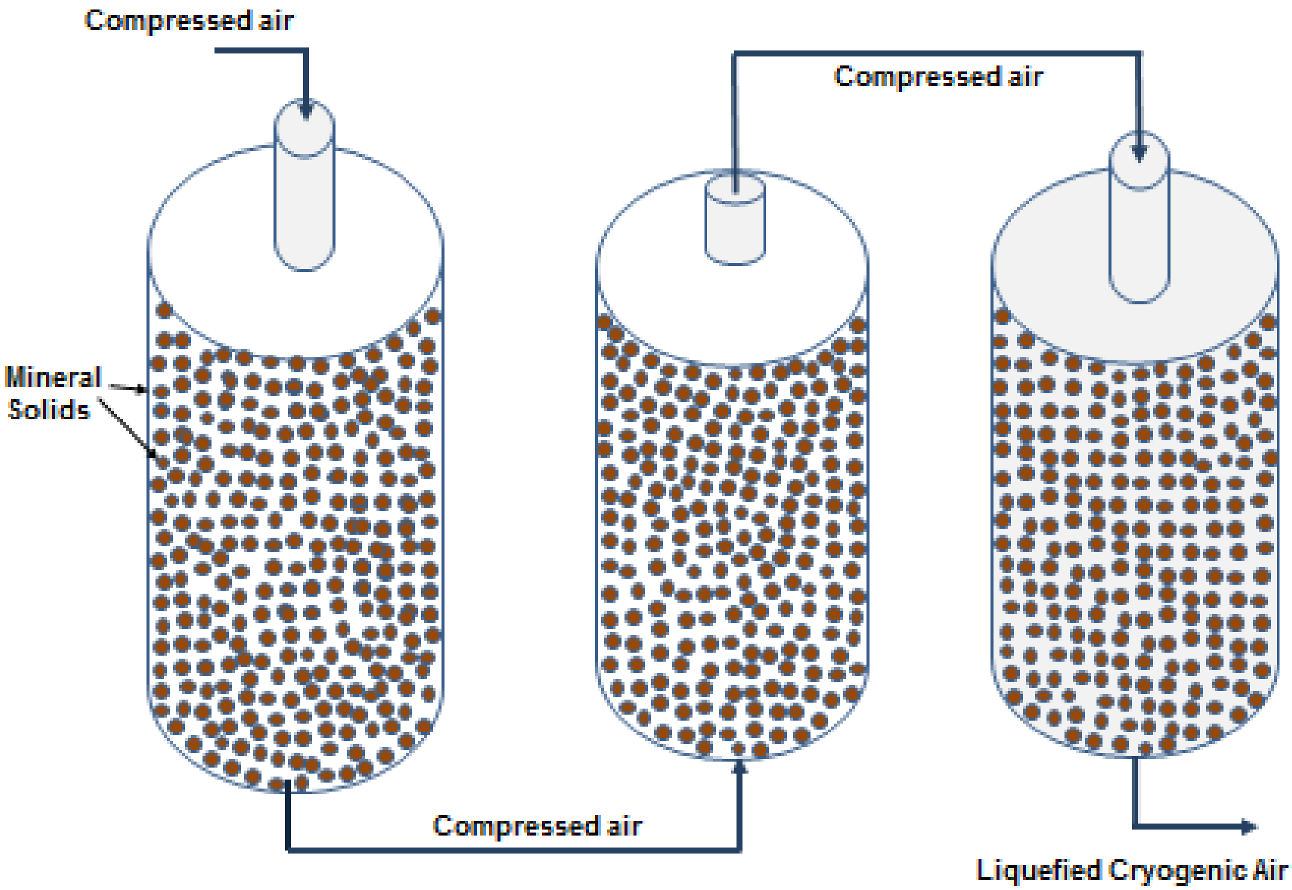
בזמן **טעינת** המערכת, אויר דחוס נכנס למגדל קריאוגני כאשר טמפרטורת אבנים בסביבות C 192- ובזמן תהליך מעבר חום עם מינרלים הופך לנוזל. אויר נוזלי יוצא מהמגדל בטמפרטורה C 187- ולחץ 50 בר. בפרמטרים הללו אויר נוזלי מתפשט בטורבינה מיוחדת ונכנס למיכל החסון של אויר נוזלי בלחץ 2.3 בר וטמפרטורה C 193-.

בזמן **פריקת** המערכת, אויר נוזלי שיוצא ממיכל ועובר תהליך דחיסה במשאבה, נכנס למגדל קריאוגני בלחץ 39 בר וטמפרטורה C 192-. במגדל מתרחש תהליך חימום והתאדות של אויר נוזלי. אויר חם אחרי מגדלי טעינה ופריקה ומחמם אויר מיוחד נכנס לטורבינת גז ויוצר חשמל עבור הרשת.

דרישות מינימום לסטודנט:

רקע חזק בתחום תרמודינמיקה ומעבר חום. יכולת לתכנת באחד מהשפות תכנות הבאות: Visual Basic, Fortran, C or C++. הכרות עם עקרונות פעולה של מערכות לאגירת אנרגיה.

Thermal Energy Absorption/Desorption Tower Operating in Charging and Discharging Regimes



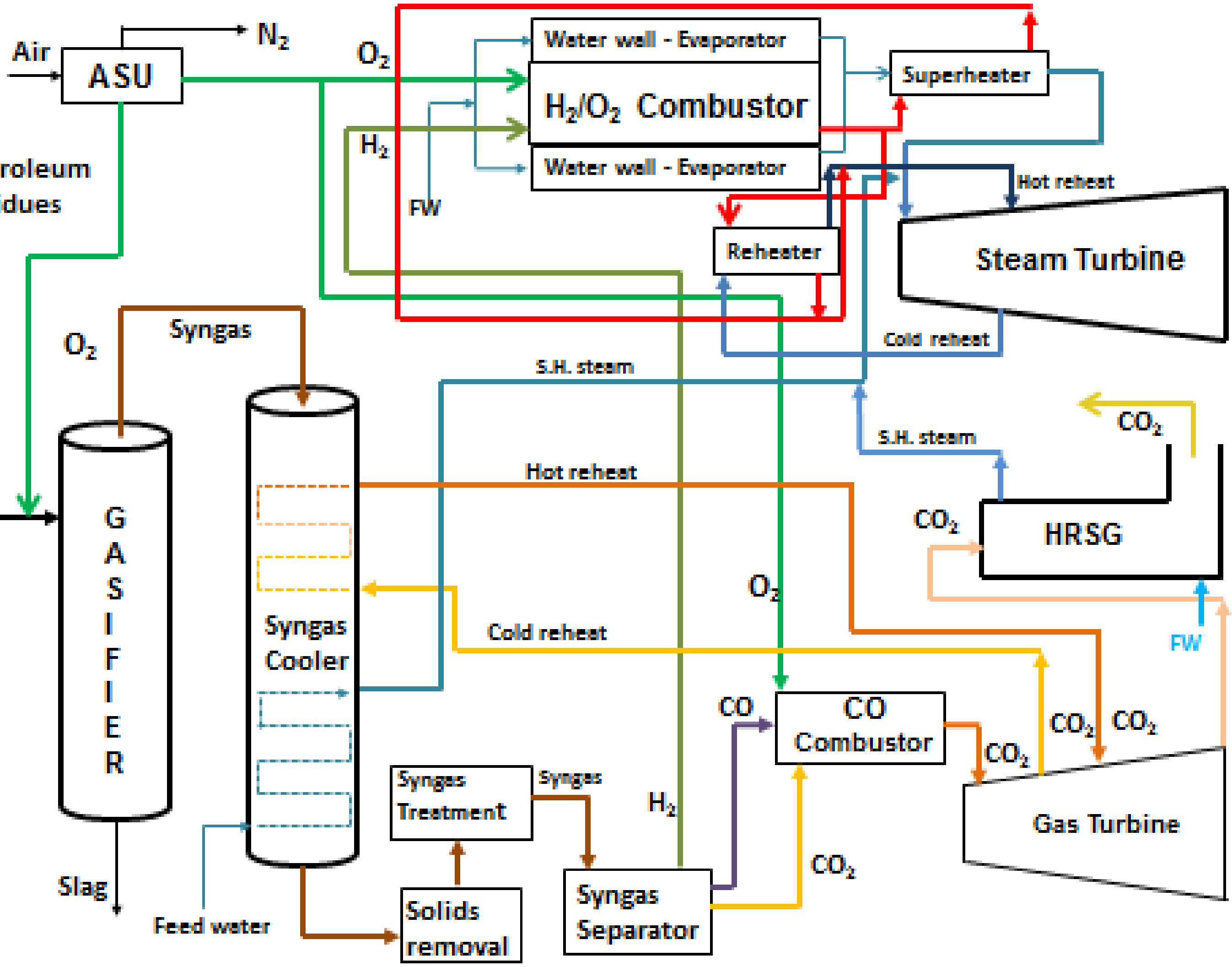
<u>7. שם הפרויקט:</u> תכן ואנליזה של מחזור משולב מסוג IGCC ששורף מימן וCO בנפרד ולא יוצר פליטות פרט לCO_2 מרוכז בעל ערך מסחרי

<u>רקע</u>
במרוץ אחרי תהליך ליצור אנרגיה חשמלית בנצילות גבוהה, עלות מתונה ומינימום של פליטות המזהמים, היום עדיין מוביל מחזור משולב (מחז"ם) שעובד על גז טבעי.
מחירים של גז טבעי עלו וירדו הרבה פעמים בעבר ולפי ערכות שונות צפויות עליות במחירי גז טבעי גם בעתיד.
יחד עם זאת, מחז"מ פולט NOx ו-CO_2 לאוויר.
קיימת חלופת ייצור אנרגיה בעלת כאפס פליטות מזהמות ובנויה על 2 מחזורים מחזור קיטורי ראשון ששורף מימן בתא שריפה מיוחד (הקיים) שמספקת חום ליצור הקיטור שחון עבור טורבינת קיטור, ומחזור קיטורי שני ששורף תחמוצת פחמן (CO) בתא שריפה של טורבינת גז. שני דלקים (מימן וCO) הופקו בתהליך הגיזוז של שאריות נפט. שאריות נפט הם תוצרי לווי של תהליכי זיקוק הנפט ומחיריהם הרבה יותר נמוכים ממחירי גז טבעי. לכן יש לבדוק האם מחז"ם על מימן וCO יכול להיות חלופה למחז"ם על גז טבעי במישור הכלכלי. הסכמה של תהליך מצורפת לדף הזה.

<u>מטרה ומשימות הפרויקט:</u>
יש לתכנן מחזור משולב שמשתמש במימן וCO בתור דלקים נפרדים ולקבוע את כל הפרמטרים שמשפעים על ביצועי מחז"ם. התכנון יבוצע ברמה קונספטואלית . בשלב ראשון יש לבצע אנליזה תרמודינמית של מחזור הכולל. צריך לחשב נצילות תרמית, ספיקות של דלקים, חמצן, מי הזנה, קיטור, הקזות, עומסים תרמים במרכיבים שונים של המחזור, צריכת אנרגיה עלי די משאבות ומדחסים, עבודות של טורבינות, לחצים וטמפרטורות בכניסה ויציאה של כל מרכיב המחזור.
נתונים של המחז"ם כוללים הספק נטו של כל המחזור, לחצים וטמפרטורות של קיטור שחון בכניסה לטורבינה, חימום חוזר, מאבה, מאייד, לחץ וטמפרטורה של חמצן ביציאה ממתקן הפרדת אויר ולחצים וטמפרטורות של מימן וCO אחרי תהליך גיזוז והפרדה.

אחרי תכן ראשוני של מחז"ם יש לבצע את אופטימיזציה של ביצועים שלו בעומס מרבי.
שלב אחרון של הפרויקט זה ביצוע אנליזה תכנו-כלכלית כדי לקבוע עלות הקמת המחז"ם, הוצאות שוטפות (O&M cost), והחזר על מחירות של חנקן והליום המתקבלים בתהליך הפרדת אויר.

<u>דרישות מינימום לסטודנט</u>: רקע בתחום תרמודינמיקה ומעבר חום. דרושה הבנה בסיסית של עקרונות פעולה של מחזורים משולבים. הבנה בסיסית של תהליכי שריפה - אתרון משמעותי. יש צורך בלימוד הנושא של תהליכי גיזוז של שאריות נפט, פחם וביומסה ברמה בסיסית .


Air
ASU
N_2
O_2
Water wall - Evaporator
H_2/O_2 Combustor
Water wall - Evaporator
Superheater
H_2
FW
Hot reheat
Reheater
Steam Turbine
Petroleum residues
O_2
Syngas
Cold reheat
S.H. steam
S.H. steam
CO_2
Hot reheat
CO_2
HRSG
G A S I F I E R
Syngas Cooler
O_2
Cold reheat
FW
CO
CO Combustor
CO_2
CO_2
CO_2
Syngas Treatment
Syngas
H_2
Gas Turbine
Slag
Feed water
Solids removal
Syngas Separator
CO_2