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The effect of hydrogen fuel on the performance and emissions of 3 kWe natural gas fuelled microturbine

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ABSTRACT

Hydrogen is an alternative fuel to power microturbines. In this work, the application of H_2 in a 3 kWe microturbine combustor is investigated. First, the combustor is tested with different molar concentrations of hydrogen in methane fuel (X_{H_2} = 5%, 10% and 20%). Afterward, the operation of the microturbine is verified using thermodynamic analysis of the microturbine cycle. The combustion of the fuels is investigated using CFD analysis. The level of gaseous emissions including (CO_2, CO, and NO_X) and the microturbine overall operability in terms of turbomachine mechanical and thermal efficiencies are compared in each case to find out the influence of hydrogen addition on the natural gas combustion in the microturbine (MT). Findings show that the application of hydrogen in the MT combustor decreases the level of CO_2 and CO emissions while increasing NO_X emissions. Despite the improvement in combustion, hydrogen could deteriorate the MT effectiveness and overall efficiency. The findings demonstrate that if the hydrogen mole percent in the fuel rises from 0 to 10, the cycle efficiency decreases from 4.73% to 4.7% and if it increases to 20 percent, the efficiency of the cycle increases from 4.7% to 4.92%.

1. Introduction

The combustion of fossil fuels results in the formation of a significant number of pollutants that endangers the life of species on earth. The use of renewable energy sources can remarkably neutralise the detrimental impacts of the conventional combustion process by offering a new affordable way of power and electricity generation. The application of hydrogen as a renewable fuel can pave the way towards the cleanliness of the combustion by offering a carbon-free renewable fuel that is free from many combustion pollutants [1].

The UK government targets the overall decarbonisation of its power generators by 2050 [2]. The use of renewable energy sources is a must to achieve this goal. The UK microturbine generator companies use diesel and kerosene fuels to power their generators. The application of these hydrocarbon fuels forms a good source of energy but it will compel the end users to pay some external costs for damaging the atmosphere [3] such as external costs [4,5]. The use of methane in microturbines as a reliable energy carrier could to some extent solve problems by extending the service intervals, reducing noises, removing the oil coolants, and providing fuel flexibility. The application of hydrogen fuel in these systems may also contribute more to the cleanliness of microturbine operations. Improvements such as increase of flame stability [6], widening the flammability [7], shortening ignition delay time [8], and soot suppression [9] are all endorsed and reported in mobile combustion systems with hydrogen fuel. It can also improve the combustion characteristics of stationary systems in terms of thermal efficiency, power cycle, and level of pollutants (CO_2, CO and hydrocarbon emissions). Recently, the application of hydrogen fuel in small-scale power generators turns out to be interesting. It must provide high efficiency, quiet operation, quick start-ups, and minimal NO_X emission [10]. The provision of hydrogen for microturbines needs a set of technologies development (injection technologies, combustor design, turbine-compressor matching). Technologies hydrogen generation also needs to be adopted from either renewable or nonrenewable sources. If these technologies are achieved and become affordable, it may benefit the microturbine in terms of power generation, higher turbomachine efficiency, emissions, and lifetime [11]. The application of any new fuel in a previously designed combustor may or may not

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need any revisions to the equipment depending on the design degree of freedom. The choice of fuel at this level could mainly influence the combustor design as well as the microturbine recuperator (heat transfer, exhaust gas composition, and temperature). Every fuel has its combustion characteristics that give off stack gas with specific conditions. Low-calorific fuels have been successfully applied in microturbine combustors. Bazooyar et al. [12] have shown that biogas can be used in a 12 kWe microturbine combustor. Ammonia can also be considered in the microturbine combustor. However, the effect of ammonia on turbomachinery is still unknown [13] and needs further studies. There are some problems associated with the deployment of ammonia in gas turbines. The main ones are increased NO emission, unstable combustion, and decreased thermal efficiency. Pashchenko [14] states that mixing ammonia with hydrogen and using integration technologies such as solar-assisted gas turbines can resolve the problems with NH_3 combustion. A new fuel can have different ignition delay times and generates different species in microturbine combustors. Nguyen et al. [15] investigated the impact of hydrogen on the ignition delay time of methane-air lean mixture and found that hydrogen can shorten the ignition timing of methane flame. Using hydrogen, the ignition delay time of methane-air can be decreased to up to a third of flames without hydrogen [16].

To manage the operation of the microturbine under the desired condition, the role of the microturbine combustor is crucial. The combustor determines the turbine inlet temperature, micro turbine output work, and emissions [12]. However, it is not controlled these parameters. The turbine inlet temperature is controlled by the turbine's control system by measuring the turbine outlet temperature and keeping it at a constant level for a given load point by alternating the fuel flow. The load point (and the output power respectively) is controlled by alternating the shaft speed to achieve the demanded power. The influence of hydrogen on methane combustion could be an increase of the temperature. Increase in spatial temperatures can increase the thermal NO [17]. However, the hydrogen effect on prompt NO is worthy of further scrutiny as it can both increase and decrease the possibility of prompt NO formation through different routes. Prompt NO is temperature-dependent pollutant [18] and an increase is expected in hydrogen flames because of the temperature. However, hydrogen could decrease the possibility of hydrocarbon undergoing Fenimore mechanism as it improves the combustion, and increases the rate of oxidisation reaction via hydrogen abstraction and β-scission reactions. N_2O pathway mechanism is not very contributive to the overall NO_X emissions of hydrogen-rich flames under turbine conditions as it forms mostly at low pressure–temperature systems [19,20]. However, how hydrogen changes this mechanism is another hot topic in hydrogen influence on the combustion characteristics of microturbines. Hydrogen can also influence the NO_X emission by changing the fluid flow and gas dynamic. It could also affect NO_X emission by decreasing the ignition delay and bringing about early autoignition. This possibly results in an increased level of NO_X in microturbine with hydrogen as an additive fuel as the residence time of the reactive mixture is now more by early autoignition [13,15]. However, the neutral [16] and decreasing [21,22] effect of hydrogen on NO_X emission are also reported in methane flames. The hydrogen as an additive could shift the axial flame peak temperature and increase the spatial temperatures, thereby affecting the NO_X emission in turbulent flames. However, no significant variation was reported in the case of mild and flameless combustion [23].

There are some challenges to designing hydrogen-fired microturbines. Early autoignition, flashback, thermoacoustic instabilities, and higher pressure are the most well-known technical challenges associated with hydrogen fuel deployment to the microturbines. This may lead to reduced lifespan and the need for effective cooling technologies. Research and development on hydrogen-fired combustor is a very potent research area for adopting hydrogen in microturbines.

In this work, the application of hydrogen as an additive to methane fuel with three proportions 0, 5, 10 and 20 mol.% in the currently available microturbine combustor is analysed using available CFD models

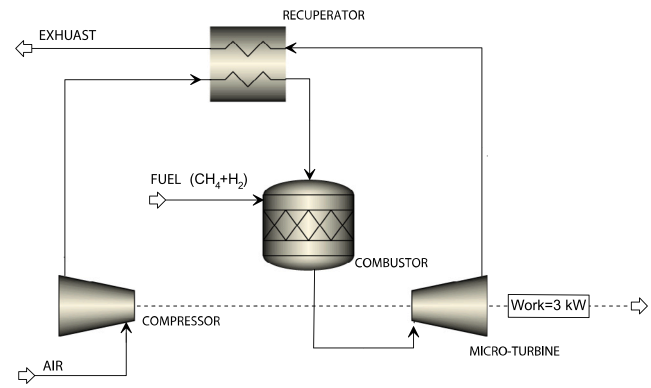

Fig. 1. The schematic of 3 kW microturbine power generator including: air compressor, recuperator, combustor, and turbine.

(turbulence, turbulence-chemistry interactions, and heat transfer). The combustor generates the required power to drive a 3-kWe turbine shaft. The influence of hydrogen on the combustor characteristics including emissions, efficiency, microturbine performance, recuperator effectiveness, and MT efficiency is verified and analysed. The goal of this study is to check if hydrogen addition in microturbine is worthy of further analysis, investment, research, and development. It also aims to find the comparison and contrast between methane and hydrogen-methane hybrid flames .

2. Modelling

2.1. Microturbine

The addition of hydrogen fuel to methane fuel is investigated at a 3 kW micro-turbine power generator. The schematic of the microturbine is shown in Fig. 1. The air passes the compressor and is pressurised to 1.8 bars (182 kPa). Then, it goes into a recuperator where it warms to 850 K via exchanging heat from the turbine exhaust. The warm air then is used to combust the fuels in the microturbine combustor and prepare a hot pressurised gas to rotate the turbine shaft. The combustor of the turbine generates 1100 K turbine inlet temperature. The air and fuel mass flow rates are 50 and 0.31 g/s, respectively.

The objective of this investigation is now to add some hydrogen to methane fuel to see how the operation of the combustor as well as the microturbine, overall, will be influenced. Adding hydrogen to methane fuel may impact the operation of the microturbine by changing the combustor exhaust gas composition and temperature (i.e., TIT), therefore the turbine output work and recuperator effectiveness in heating the compressed air. For this study, it is assumed that the turbine output work remains constant, therefore recuperator effectiveness, combustor outlet temperature, and composition under the influence of the hydrogen addition is studied. For analysis of these variables, the operation of the combustor is evaluated via CFD modelling and the operation of the microturbine overall is investigated by Aspen plus software.

2.2. Combustor

The cut-plane view of the combustor is given in Fig. 2. It is a swirl stabilised combustor including a serrated liner, 46 mm in diameter and 135 mm in length. The throat of the combustor is a 10 cm pipe-type duct that is connected to the liner via a combustor head, a conic wall angled 60° from the combustor centreline. The liner body is serrated with 18 series of rings 1 mm in diameter for improving heat transfer from the combusting mixture to the air in the outer casing and contributing to the combustion efficiency. The thickness throughout the combustor body was 3 mm.

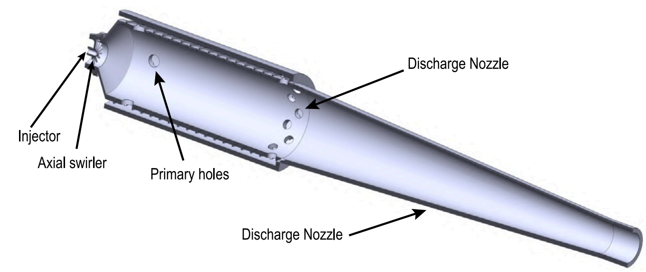

Fig. 2. The cut-plane view of the combustor equipped with 1-injector, 2-axial swirler, 3-currogated liner, 5- A series including 4 primary holes, 6- A series including 16 dilution holes.

The combustor is air recuperated, located inside the microturbine plenum. The pressurised air at 1.8 bar is forced into the combustor through the combustor swirler and casing. The design of the combustor allows 3% pressure drop overall. Almost 8% of the recuperated air is coming through the swirler and 92% goes inside the casing where it is divided via primary (16%) and dilution holes (73%).

2.3. CFD analysis

The operation of the combustor with different fractions of hydrogen in methane fuel is investigated using CFD modelling. The geometry of the combustor is created using Solidworks and is processed using Ansys modules. Ansys Fluent is used to setup the models and run the simulations. The fluid flow is turbulent as it passes over the combustor parts. The Reynold-Average-Navier–Stokes (RANS) is used to resolve the closure of the turbulence. For this simulation, the k-ϵ shear stress transport (SST) model is employed to deal with the adverse pressure gradients [24–26]. For the chemistry of the combustion, GRI MESH III is used [27]. The flamelet concept is used to resolve the chemistry-turbulence interactions [28]. For this test, 32 diffusion flamelets with 64 grid points are generated. A transport equation for mixture fraction is solved to find the mass fractions. The Discrete ordinates model the heat radiation of gas to the combustor walls [29]. Conjugate heat transfer is used to model the heat transfer within the fluid and combustor walls. However, natural convection with air at 850 K with heat transfer coefficient= 10 W/m^2.K is used to model the heat transfer from the external walls (external walls of the casing and discharge nozzle) of the combustor to the recuperated air in the plenum. Concentrations of species except NO_X emission are obtained from GRI Mesh 3 combustion mechanism. NO_X emission is obtained from modelling the thermal, prompt, and N_2O pathway mechanism [20]. Formation of NO_X through thermal, prompt, and N_2O pathway mechanisms are considered for this simulation. Transport equations for three main NO_X species (NH_3, NO, and N_2O) are solved for the prediction of NO_X for CH_4/H_2 mixture. To consider the effect of turbulence, a Gaussian probability density function (PDF) is used to find the fluctuations of reaction source terms. The extended Zeldovich mechanism is employed for thermal NO_X, and DeSoete formulations are employed for prompt NO and N_2O pathway in the NO reaction source term.

A 3-d computational domain including a 13 M grid for CFD simulation is extracted from the body of the combustor. The boundaries are defined: mass flow rates for the three inlets (fuel, swirl, and (primary+dilution)) and pressure outlet for the combustor exit plane. The body of the combustor is considered stainless steel with a thickness of 3 mm. The solid parts of the combustor are also meshed and included in the simulations.

A steady solver via the least square cell-based finite volume schematic is developed on a simple scheme for pressure–velocity coupling. The standard scheme for pressure and second-order upwind for the transport equation are chosen to solve the differential equation in the computational domain. The simulation is considered complete and results are extracted from the simulations when area-averaged temperature, velocity, and emissions become constant at the combustor outlet plane. Different numbers of grids are also tested for verification of the simulation. The accuracy of the results in a domain with more than 7 M elements is acceptable as no significant difference is obtained by increasing the number of grids. The results of the simulations for 13 M are reported.

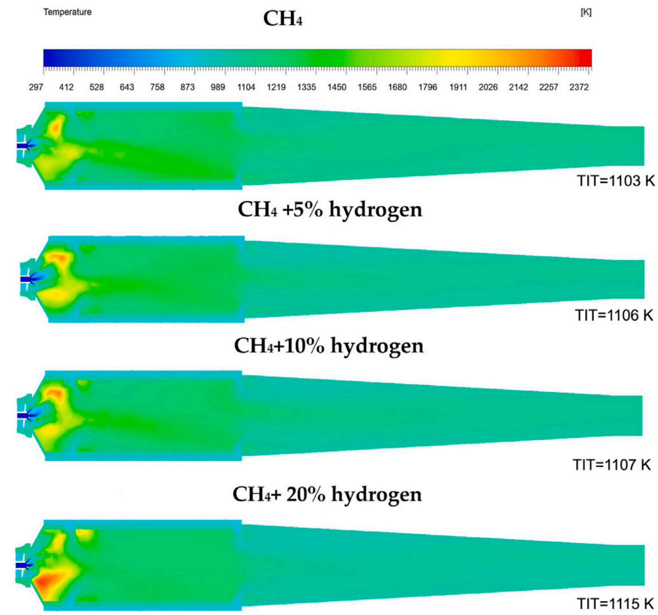

Fig. 3. Temperature profile contours at the same midplane of the combustor fed with CH_4, CH_4+ 5% H_2, CH_4+ 10% H_2, and CH_4+ 20% H_2.

3. Results

3.1. Temperature profile

First, the influence of hydrogen fuel on the combustion of methane on the spatial temperatures is evaluated. In this analysis, the fuel flow rate injected into the combustor is kept constant and only the hydrogen and methane fuel mole fractions are changed. Fig. 3 gives the temperature contours of the combustor at the YZ mid-plane for methane and methane including 5, 10, and 20 mol.% hydrogen. It could be readily seen from these graphs that the addition of hydrogen in the methane increases the maximum temperature in the combustor. However, the solid temperature is still the same order of magnitude.

The maximum temperature observed for fuel hydrogen content 20, 10, 5 and 0% is 2372, 2272, 2285, and 2205 K, respectively. This maximum temperature is observed at the primary zone of the combustor in the fuel and swirl air mixture. The local temperature of the mixture goes down further downstream in the combustor and reaches the desired TIT for the microturbine. The turbine inlet temperature for CH_4, 5% H_2-95% CH_4, 10% H_2-90% CH_4, and 20% H_2-80% CH_4 is 1103, 1106, 1107, and 1115, respectively. 80% CH_4- 20% H_2 flame has the highest peak temperature which is likely due to the higher heating values of the hydrogen than methane. Replacing methane with hydrogen could increase the spatial and peak temperature of the combustor. This trend demonstrates that blade cooling technologies need to be further improved if hydrogen fuelled microturbine is developed. The flame position is slightly shifted downstream and lift-off length decreases comparatively in flames with more hydrogen. This is probably due to the high reactivity and higher diffusivity of hydrogen. Hydrogen in fuels can penetrate downstream, react with fresh warm air and shortening the flame lift-off length. In this combustor, the temperature

Table 1
Change in the level of gaseous emission by addition of hydrogen (%).

H_2 [%]	CO_2 (decrease%)	CO (decrease%)	NO_X (increase%)
5	1.46	45	21
10	2.256	43	22
20	6	47	23

of the cold flow of the fuel stream should reach the autoignition temperature. Note that fresh cold fuel mixture containing more hydrogen requires more heat and energy for the occurrence of chain branching reaction as the hydrogen autoignition temperature is slightly more than methane. However, when hydrogen is added, the mixture temperature in the vicinity of the nozzle is warm enough for ignition of whatever the fuel, nullifying the influence of higher autoignition temperatures in hydrogen-rich mixtures. The results here indicate that the reactivity and diffusivity of hydrogen are more influential in the flame characteristics of hydrogen flames under microturbine conditions.

3.2. Pollutant formation

Hydrogen can also impact the pollutant formation of the methane fuel in the combustor. It can change the chemistry of combustion and spatial temperatures. For analysis of hydrogen on the level of pollutants, the level of CO_2, CO, and NO_X emissions are reported at the combustor outlet plane (the volumetric percentage of flue gas for carbon dioxide and mg/m^3 for CO and NO_X emissions). The levels of pollutants are standardised based on 15% O_2 in the dry flue gas and reported in Fig. 4.

Hydrogen addition to methane can improve combustion by decreasing the level of CO and CO_2 emissions. The combustion of hydrogen increases the water vapor of the flue gas, thereby decreasing the percentage of CO_2. The hydrogen addition can also increase the combustion temperature and burning of the resultant hydrocarbons. Hydrogen can increase the level of NO_X emission, possibly due to thermal NO formation. An increase in temperature resulting from adding hydrogen facilitates the dissociation of nitrogen and NO_X formation. This shows that state-of-the-art cooling technologies or air-staging techniques might be required to minimise the formation of NO_X emission.

Table 1 gives the percentage of decrease or increase of gaseous emissions by adding hydrogen to methane fuel. The level of CO_2 decreases 1.46%, 2.256%, and 6% (7.2% reported by Pashchenko [30]) by adding 5, 10, 20 mol percentage of hydrogen to methane fuel. A decrease of 45, 43, and 47% in the level of CO was observed when the methane fuel includes 5, 10, and 20 mol.% hydrogen. The NO_X increases by 21, 22, 23% for hydrogen content 5, 10, and 20 mol.% in the fuel.

3.3. Microturbine operation

The impact of hydrogen on the overall performance of the 3 kWe MT is investigated using T-S plot of the micrturbine. For this analysis, the operation of the MT is considered to match a standard Brayton cycle. A Gibbs reactor, turbine, compressor, and heat exchanger are chosen to show the operation of turbomachinery, the circulating gas thermochemical state, and equilibrium diagrams. The turbine and compressor are assumed isentropic with 98% mechanical efficiency. The combustor and exchanger were modelled adiabatic without zero heat transfer.

The MT is an open Brayton cycle that can produce 3 kWe net power output for domestic heat and electricity generation (Fig. 1). The MT shaft can drive the air compressor as well as a 3 kWe free turbine. The operation of the MT cycle is used here for drawing a comparison between natural gas and natural gas-hydrogen hybrid fuel. Fig. 5 gives the T-S diagram of the MT cycle in a close format.

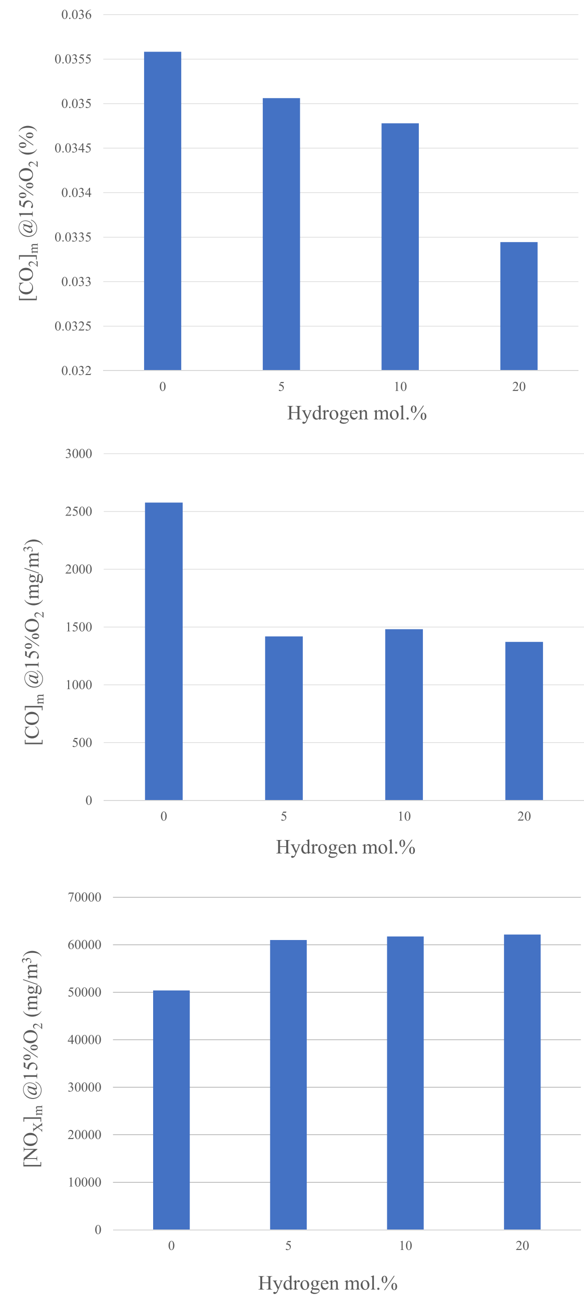

Fig. 4. CO_2 [mol.%], CO[mg/m^3], and NO_X [mg/m^3] corrected based on 15% O_2 in the flue gas at the combustor outlet plane with CH_4, CH_4+5%H_2, CH_4+10%H_2, and CH_4+20%H_2.

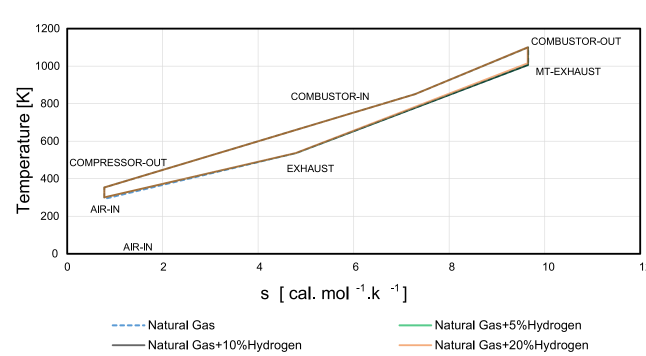

Fig. 5. T-S diagram of MT with different concentrations of hydrogen in natural gas.

Table 2
Change in the net power output of turbine by addition of hydrogen (%).

H_2 mol fraction []	0%	5%	10%	20%
Turbine inlet temperature [K]	1100	1102	1104	1110
Net power output [kW]	3	3.02	3.05	3.1
Cycle efficiency [%]	4.73	4.71	4.7	4.95
Recuperator effectiveness []	0.85	0.84	0.84	0.83

The T-S diagram of all case studies matches each other. The effectiveness of the recuperator and the thermal efficiency of the cycle are calculated for the different hydrogen content of fuels for further analysis of the cycle. The hydrogen fuel can change the recuperator's effectiveness and overall efficiency. The recuperator effectiveness decreases from 0.76 to 0.75 as 20% mol hydrogen is added to the methane fuel. The cycle efficiency also decreases from 5.46% to 4.23% as 20% of methane is replaced with hydrogen. The results for the reduction in the cycle efficiency are because of the same output work considered for the microturbine. In all cases considered, when hydrogen is added and replaced with methane, more heat is generated. If the output work is considered constant for whatever the hydrogen concentration is, reductions in the cycle efficiency overall are expected. The added heat of combustion is lost somewhere in the cycle because of the irreversibility and entropy generations.

The simulation result shows that if the cycle is considered ideal and all hydrogen heat is converted to work by the turbine, the network output work of the cycle is increased. Table 2 gives the result of turbine inlet temperature, net power output, cycle efficiency, and recuperator effectiveness when hydrogen is added to the microturbine. The turbine inlet temperature and net power output have an increasing trend in general. However, the cycle efficiency is decreased when hydrogen is added and then increases for a higher percentage of hydrogen (above 10%). Increase in the hydrogen-fuelled gas turbines is also reported around (7% by Pashchenko [31]) for overall efficiency if a gas turbine operation is integrated with the methane reformer.

To illuminate the influence of hydrogen addition in the microturbine performance, the material and energy balance through the microturbine cycle is represented in Fig. 6. Hydrogen can change the enthalpy balance of the combustor, turbine, and connected flow streams to these units. If the mass flow rate of the fuel to the combustor remains constant, the flow of enthalpy to the combustor changes as the heat of combustion and enthalpy flow of the fuel stream changes. This results in different turbine inlet temperatures (table 2). The results show that turbine inlet temperature has an increasing trend with hydrogen mass input. This also increases the net power output from the cycle for whatever percentage of the hydrogen. Hydrogen can change the heat of combustion of natural gas from −22.16 kW to −22.26 kW, 22.37 kW, and 22.63 kW. This extra heat generated in the microturbine combustor is partly used in the expander to generate extra work and partly used in the recuperator for heat recovery and increase of the overall cycle efficiency. Note that the effect of this extra heat is neglected in this study and just an increase in the net power output is considered. Using this figure, hydrogen decreases the overall cycle efficiency for up to 10% concentration, and for any concentration more the cycle efficiency increases with hydrogen deployment to the turbomachinery. Current figures show that energy loss from the hydrogen-fuelled microturbines is somewhat higher than from natural gas. This heat needs to be somehow recovered to add to the cycle efficiency and design of a system that may experience efficient improvement with hydrogen fuel.

4. Conclusion

In this work, the effect of hydrogen addition into the microturbine power generators is investigated. A 3 kWe case study microturbine system is chosen and the influence of four different types of fuels is

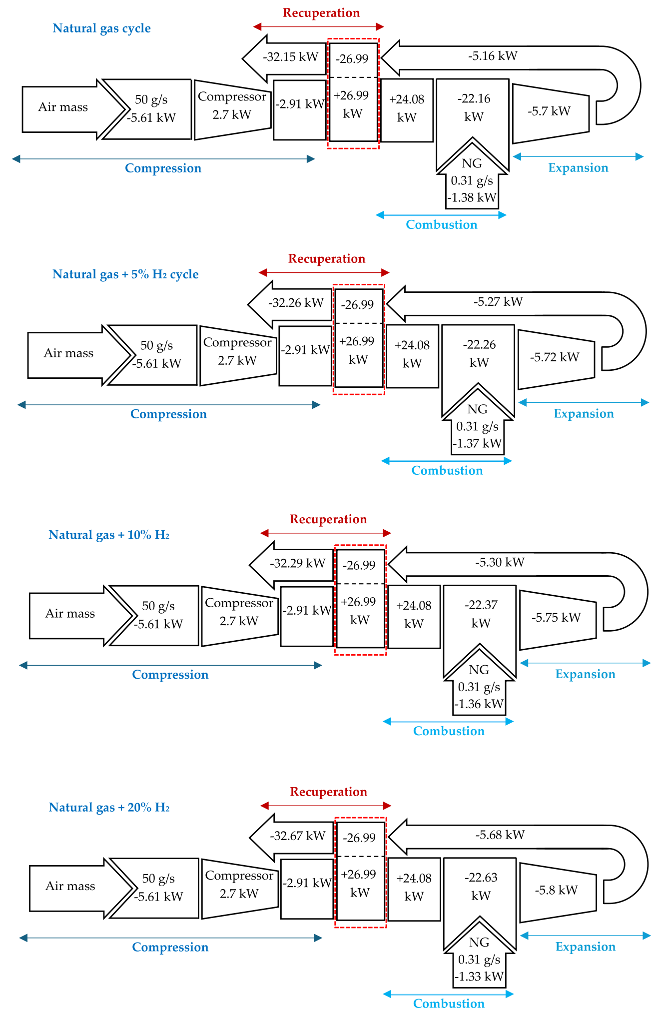

Fig. 6. Material and energy balance for different concentrations of hydrogen in natural gas through the microturbine cycle.

studied. The pure methane, methane with 5, 10 and 20 mol.% hydrogen are analysed in the selected MT turbine without any improvement or adding any change in the MT system. The combustor and recuperator of the system are more under the influence of any newly implemented fuel. The operation of the combustor is analysed using CFD simulation. The RANS is used to resolve the turbulence in the 3d domain considered for the combustor. The turbulence-chemistry interaction is handled by the flamelet concept. The verified CFD results show that hydrogen can improve the combustion of methane by increasing the spatial temperature in the primary zone of the combustor. CO_2 emission decreases by 6%, 2.26%, and 1.46% with 20, 10 and 5 mol% hydrogen content in the fuel. CO decreases by 47, 43, and 45% with 20, 10 and 5 mol% hydrogen in the methane. However, NO_X emission of the combustor increases by 23, 22, 21% as 20, 10, and 5 percent of hydrogen is added to methane. The effect of hydrogen on the operation of the MT is also evaluated. The findings demonstrate that hydrogen decreases the overall MT efficiency and recuperator effectiveness, although it promotes combustion. These numbers are obtained when the hydrogen-fuelled turbine is aimed to generate 3 kWe power whatever the H_2 percentages are. If hydrogen allows to increase the net cycle power output and extra heat produced in the cycle is not wasted, the efficiency of hydrogen assisted cycle depends on the concentration of the hydrogen. Our findings show that if the concentration of hydrogen increases up to 10%, the cycle efficiency decreases from 4.73% for natural gas fuelled turbine to 4.7% for 10% H_2-90% natural gas-fuelled turbine. If the hydrogen concentration increases to 20%, the cycle efficiency increases from 4.7% to 4.95%. This study confirms that hydrogen can be used in the MT combustor as an additive for methane fuel. It can improve the combustion of methane by decreasing CO_2 and CO emissions. However, NO_X emission is increased, and overall cycle efficiency is declined by adding hydrogen to methane fuel. Despite the fact that hydrogen fuelled microturbines could decrease the carbon emission such as CO_2 and CO, they might still suffer from increased NO_X emission and deteriorated overall cycle efficiency which can be further improved by the design of a modern blade cooling technologies, advanced air-staging techniques, and more effective recuperation methodology.

CRediT authorship contribution statement

Abolfazl Jomekian: Writing – review & editing, Writing – original draft, Resources, Funding acquisition. **Bilal Naji Alhasnawi:** Software, Resources, Project administration, Funding acquisition, Formal analysis. **Bahamin Bazooyar:** Writing – original draft, Visualization, Data curation, Conceptualization. **Ali Nabavi:** Visualization, Validation, Supervision. **Hirbod Varasteh:** Data curation, Formal analysis, Software, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data used for this research and prepatation of this article can be accessed from Brunel University of London repository at: https://doi.org/10.17633/rd.brunel.26491492.v1.

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