Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Seasonal energy performance assessment of a hybrid HVAC system driven by solar and biomass energy for space heating and cooling in residential buildings

To cite this article: M Dongellini *et al* 2024 *J. Phys.: Conf. Ser.* **2766** 012100

Seasonal energy performance assessment of a hybrid HVAC system driven by solar and biomass energy for space heating and cooling in residential buildings

M Dongellini[1], C Naldi[1], C Moser[2], S Varga[3], J Soares[3] and GL Morini[1]

[1] Department of Industrial Engineering, University of Bologna, Bologna, 40136, Italy
[2] Institute of Thermal Engineering, Graz University of Technology, Graz, 8010, Austria
[3] Department of Mechanical Engineering, University of Porto, Porto, 4200-465, Portugal

Email: matteo.dongellini@unibo.it

Abstract. The H2020 project Hybrid-BioVGE aims to develop a sustainable HVAC system concept for buildings' climatisation entirely based on renewable energy sources. The Hybrid-BioVGE system provides space heating/cooling and DHW production of small- and medium-scale buildings and deploys solar and biomass heat as energy inputs. During the heating period, thermal energy is provided directly by solar thermal collectors and a biomass boiler. The cooling energy demand is met by a thermally-driven ejector cycle based on a Variable Geometry Ejector (VGE), which adjusts its geometry according to two degrees of freedom. A demonstrator of the Hybrid-BioVGE system was designed and installed in a residential building in Porto (Portugal). The demonstrator's seasonal energy performance was assessed numerically by a simulation model implemented in TRNSYS. Simulation results show that up to 98% of the system energy input is provided by renewables during the heating season, with a solar fraction higher than 60%. Conversely, the system energy performance is lower than expected during the cooling season due primarily to the limited performance of the heat rejection loop.

1. Introduction

Solar-driven ejector technology is a promising solution to decarbonise the building sector. Ejector cooling cycles can be used in many applications because they can meet the cooling energy demand by exploiting a low-grade renewable source [1]. Even though this kind of system presents several benefits, such as low cost and simplicity in construction and installation, the ejector Coefficient of Performance (*COP*) is relatively modest, and the cycle efficiency is limited by high ambient temperature values [2]. Moreover, fixed-geometry ejectors are typically employed, and consequently, the maximum performance can be achieved only in a narrow range of operating conditions [3].

Within this context, under the Hybrid-BioVGE project, the concept of an HVAC system driven by renewable energy was designed and installed in a residential building. The system is driven by heat during both the heating and cooling seasons since the cooling energy demand is met by a variable geometry ejector (VGE) cycle. The VGE can adjust its geometry automatically with two degrees of freedom to improve the chiller performance under floating working conditions. In this work, the main features of the Hybrid-BioVGE demonstrator are described, and the system's seasonal energy performance is evaluated by a dynamic numerical model implemented with TRNSYS 18

Journal of Physics: Conference Series **2766** (2024) 012100 doi:10.1088/1742-6596/2766/1/012100

2. Description of the Hybrid-BioVGE concept and demonstrator

The Hybrid-BioVGE system exploits solar energy as the primary energy source. Heat is obtained from solar thermal collectors and is used for space heating and DHW production. During the summer, the building's cooling load is met by a solar-driven ejector cycle based on a VGE. Over both seasons, a biomass boiler operates as backup. To maximise the deployment of solar energy, three thermal energy storages (TESs) are present. First, heat is stored in a large sensible TES coupled to the solar field. The tank is connected to the heating distribution loop and the ejector generator. DHW is stored in a smaller sensible TES, coupled to solar thermal collectors by an immersed coiled heat exchanger. Finally, a latent TES tank filled with encapsulated PCM modules and water decouples the cooling cycle evaporator and the building emitters. A simplified layout of the Hybrid-BioVGE concept is shown in figure 1.

A demonstrator of the Hybrid-BioVGE system was installed in a single-family house built in Porto (Portugal) in 2020. The building consists of four storeys: an unheated basement, where the technical room is present, and three conditioned floors. The building's net floor area and conditioned volume are equal to almost 185 m^2 and 430 m^3, respectively. The building envelope components are characterised by high-quality thermal properties. The average U-value of opaque elements, such as external walls, ceilings and the roof, ranges between 0.3 and 0.4 W/m^2K. Double-glazing windows filled with argon and having a U-value equal to 1.67 W/m^2K are installed. In figure 2, a view of the building is depicted. Additional data on the building can be found in [5] and are not reported here for the sake of brevity.

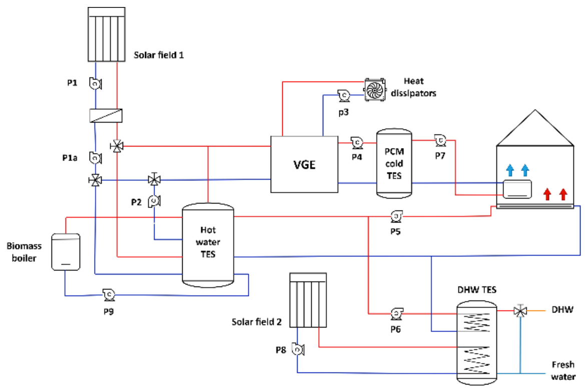

Figure 1. Layout of the Hybrid-BioVGE system.

Figure 2. View of the demonstrator building.

The VGE cooling cycle is the most innovative element of the HVAC system. According to current operating conditions, the ejector can adjust its geometry with two degrees of freedom. The primary nozzle throat area and exit position can be varied simultaneously using linear stepper motors, which adjust the arrangement of a movable spindle and the nozzle itself. The spindle and nozzle positions are adjusted to maximise the ejector *COP* and the secondary stream mass flow rate. The ejector geometrical features, such as spindle shape and full travel length, mixing section area and diffuser length, were designed with a CFD model implemented in the Ansys environment. The optimal values of the entrainment ratio and *COP* in correspondence with all possible working conditions were also evaluated with CFD simulations. The obtained VGE performance data are reported in [6]. Since water is used as heat transfer fluid, brazed plate heat exchangers were selected as generator, condenser and evaporator of the ejector cooling cycle.

As pointed out in figure 1, two solar fields are present in the demonstrator. Flat plate solar thermal collectors with a slope of 35° and oriented to the South are installed on the building's roof. The largest field presents nine collectors, while the smallest one is dedicated to DHW production and has only two panels. Hot water is stored in a 300-litre TES placed on the roof. A commercial pellet boiler with a nominal heating capacity of 12 kW is used as a backup heater. The hot TES has a volume of 1000 litres and presents four couple of ports for the connection to the other components of the system. The cold latent TES has a capacity of 600 litres and is filled with rectangular PCM modules for about 33% of its volume. The salt hydrate ATS 15, characterised by a latent heat of 180 kJ/kg and a phase change range equal to 12-17°C, is used to increase the heat-storing capacity of the TES. The cooling cycle condensation heat is rejected to the ambient air by two water-to-air heat dissipators connected in parallel. The dissipating capacity of these units is influenced strongly by the ambient conditions: the higher the outdoor temperature, the lower the heat rejection capacity.

The seasonal energy performance of the Hybrid-BioVGE demonstrator was evaluated numerically by means of a dynamic model implemented with TRNSYS 18. The simulation model includes all the components of the HVAC system described previously and the building, modelled with the plugin TRNBuild. It is worth mentioning that the model of an ejector cooling cycle is not included in the TRNSYS libraries. For this reason, a new Type was programmed in the FORTRAN language. This component is based on a performance map approach. It calculates the ejector performance (i.e., heat transfer rate at generator, condenser and evaporator sides, water temperature at the heat exchangers outlet) given the values of entrainment ratio and *COP* as inputs. Hourly climatic data were taken from the TRY of Porto, included in the database Meteonorm. According to these data, the heating season ranges from 27th October to 30th April, while the cooling period is extended from 1st May to 26th October.

3. Results and discussion

The energy balance of the Hybrid-BioVGE demonstrator for the heating period is shown in table 1. Simulation results outline the promising performance of the Hybrid-BioVGE concept during the heating season for locations characterised by a mild climate, as in Porto. Solar thermal collectors provide the largest share of the system energy input. In fact, the system solar fraction of the heating season SF_h, defined as the ratio between the useful heat collected by both the solar fields ($Q_{sol,h}$) and the overall system's energy input, is equal to 61.5%. Furthermore, the building energy demand for space heating and DHW production (namely Q_{sh} and $Q_{DHW,h}$) are entirely met by the HVAC system, ensuring optimal comfort conditions for the building's tenants. Auxiliary heat from the biomass boiler is needed for a significant part of the season: the backup heater supplies about 2500 kWh of thermal energy to the HVAC system, corresponding to a wood pellet consumption of almost 650 kg. In general, the operating time of the Hybrid-BioVGE system is equal to almost 2050 hours during the season.

Table 1. Energy balance of the Hybrid-BioVGE demonstrator during the heating season.

$Q_{sol,h}$ (kWh)	$Q_{boil,h}$ (kWh)	Q_{sh} (kWh)	$Q_{DHW,h}$ (kWh)	$Q_{loss,h}$ (kWh)	$W_{el,h}$ (kWh)	SF_h
3877	2464	3321	2273	747	89	0.615

Moreover, numerical results show that the thermal losses from the system components $Q_{loss,h}$ are limited to about 15% of the useful energy provided to the building over the season. Finally, the electric energy consumption of the circulating pumps and the system's auxiliaries $W_{el,h}$ is equal to 89 kWh, corresponding to a minimal share of the heat supplied to the building. In conclusion, the Hybrid-BioVGE demonstrator presents a seasonal energy performance during the heating season that is higher than expected for a climate characterised by a predominant cooling demand.

The energy balance of the Hybrid-BioVGE system throughout the cooling season is shown in table 2. Unfortunately, the system's seasonal energy performance is much lower than expected. The solar fraction SF_c is equal to 44% over the cooling period: the biomass boiler operation is extremely frequent, and the corresponding pellet consumption is higher than 1500 kg. The critical feature of the system is the ejector cooling cycle, characterised by poor efficiency: the seasonal performance factor (*SPF*) of the VGE is equal to 0.144. The performed simulations show that the VGE performance is penalised strongly by the heat rejection loop. Since the heat dissipators' capacity decreases for high ambient temperature values, the condensation temperature increases above 30°C for the largest share of the cooling season. Therefore, the chiller operates with a poor cooling capacity and *COP* even for high values of the generation temperature. Furthermore, when the condensation temperature increases beyond 40°C, the cooling cycle is switched off because critical conditions cannot be reached. Due to this intermittent operation, only 60% of the building cooling energy demand can be satisfied by the system, resulting in overheating conditions within the rooms. In addition, the low cooling capacity of the ejector cycle results in a prolonged operation to meet the building cooling load: the total operating time of the VGE chiller and its auxiliaries is equal to about 314 hours. Therefore, the electric energy consumption of the auxiliaries $W_{el,c}$ is much higher than expected. Data from table 2 show that *Wel,c* is equal to 544 kWh, corresponding to about 60% of the useful cooling energy supplied to the building (Q_{sc}).

Table 2. Energy balance of the Hybrid-BioVGE demonstrator during the cooling season.

$Q_{sol,c}$ (kWh)	$Q_{boil,c}$ (kWh)	Q_{sc} (kWh)	$Q_{DHW,c}$ (kWh)	$Q_{loss,c}$ (kWh)	$W_{el,c}$ (kWh)	SF_c
4183	5300	872	2069	818	544	0.440

The simulation results analysis shows that the incapability to reject the condensation heat properly penalises the ejector cycle efficiency and, consequently, the system's seasonal performance. In order to optimise the Hybrid-BioVGE system operation during the cooling season, the heat dissipation loop should be revisited. For instance, different dissipators could be employed (i.e., cooling towers), or a warm water stream could be used directly in the condenser.

4. Conclusions

In this article, the concept of an innovative HVAC system proposed by the H2020 project Hybrid-BioVGE is presented. The system is designed to provide space heating, space cooling and DHW production for small- and medium-scale buildings and is driven by solar energy and biomass. The building’s cooling energy demand is met by a heat-driven ejector cycle based on a Variable Geometry Ejector (VGE). The dynamic model of a demonstrator installed in a single-family house was implemented in TRNSYS 18, and the system’s seasonal energy performance was assessed numerically.

During the heating operating mode, more than 98% of the system’s energy input is provided by renewable energy, with a solar fraction higher than 60%. On the other hand, the system’s energy performance during the cooling period could be improved strongly. The VGE cycle presents a seasonal performance factor of 0.144; moreover, the building cooling demand cannot be met entirely. In conclusion, the Hybrid-BioVGE concept could be a promising solution for the climatisation of buildings in locations characterised by a mild climate. Still, a deep re-design of both the heat dissipation loop and system’s control strategy is needed to improve the system’s efficiency. For example, a water-cooled condenser coupled to a cooling tower or used to pre-heat hot water in gyms or pools could guarantee lower values of the condensing temperature and, therefore, a higher efficiency of the system.

Acknowledgements

This paper is supported by European Union’s Horizon 2020 research and innovation programme under grant agreement N° 818012, project Hybrid-BioVGE and RdS PTR 2022–2024 agreement between MASE and ENEA, Research objective “Tecnologie per la penetrazione efficiente del vettore elettrico negli usi finali”, Work package 4, LA8 and LA9.

References

[1] Allouche Y, Varga S, Bouden C and Oliveira AC 2017 *App. En.* **190** 600-611
[2] Braimakis K, 2021 *Ren. En.* **164** 566-602
[3] Shahzamanian B, Varga S, Soares J, Palmero-Marrero AI and Oliveira AC 2021 *App. Th. Eng.* **195** 117177
[4] Van Nguyen V, Varga S, Soares J, Dvorak V and AC Oliveira 2020 *Int. J. Ref.* **113** 187-195
[5] Moser C and Schranzhofer H 2020 *H2020 Hybdrid-BioVGE Project Deliverable Report 2.1*
[6] Varga S and Soares J 2020 *H2020 Hybdrid-BioVGE Project Deliverable Report 3.1*