Applied Thermal Engineering 109 (2016) 803–808

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

# A high efficiency 20 kWe microcogeneration unit based on a turbocharged automotive gas engine

P. Capaldi

*Istituto Motori – National Research Council, Largo Barsanti e Matteucci 8, 80125 Naples, Italy*

## HIGHLIGHTS

- A new microcogenerator based on a high efficiency down sized engine.
- The plant gives a clear efficiency gain for a wide range of the electric load.
- A spark ignition engine derived from a Diesel unit is more robust and reliable.

## ARTICLE INFO

*Article history:*
Received 3 September 2015
Revised 29 February 2016
Accepted 4 March 2016
Available online 9 April 2016

*Keywords:*
Microcogeneration
Micro-grids
Distributed generation
Natural gas

## ABSTRACT

The paper deals with the design and the overall performance of 20 kWe cogeneration plant, suitable for local energy conversion and based on a wide-spread automotive internal combustion engine. The manuscript starts by defining the state of art of commercial cogenerators of the same power, underlining that a higher electric efficiency, which leads to a lower heat to electricity ratio, can elevate the annual service factor and the economic effectiveness while reducing $CO_2$ emission. Then is reported the concept which leaded to the specific choice of a small displacement, high boosted engine (in terms of brake mean effective pressure) made to obtain a significant improvement of the engine global efficiency especially at partial load (if compared to most of the best competitors) and consequently a higher electric efficiency. The unit has been derived from a turbocharged Diesel engine, then converted into a spark ignition methane/natural gas system and finally coupled with an asynchronous liquid cooled generator together with high efficiency heat exchangers and some unconventional heat recovery devices in order to maximize thermal efficiency. The whole system, after being placed into a sealed capsule expressly designed to reduce heat losses and noise emission, has been tested as an electricity/heat generation plant to know its running global behavior.



## 1. Introduction

Small cogenerative systems seem to be an interesting solution to become a smart way of energy supplying for buildings and small industrial/commercial activities, capable to reduce fuel needs and $CO_2$ emissions. Actually there are many plants available on the European market most of them belonging to the 20 kWe power class (such as LichBlick-VolksWagen EcoBlue [1], Viessmann Vitobloc 18/36 [2] and Yanmar CPW-25 [3]). These systems have been conceived as 4-cylinder, N.A. (naturally-aspired), I.C.E (internal combustion engines), directly coupled to an electric generator and a set of heat exchangers, in order to recover heat from cooling-lubricating fluids and exhaust gases. The rotational speed is set at 1500 rpm (if a 4-poles asynchronous generator is adopted [1,2]) in order to match the local grid frequency of 50 Hz; different speeds can be chosen if an inverter is adopted (1800 rpm in case of [3] together with a permanent magnet synchronous generator). The choice of a limited rotational speed is made to reduce mean piston speed and noise, while obtaining a longer running life. These plants have remarkable performances, if compared to their small power, both in terms of electric efficiency (up to 32% declared) and P.E.R. (Primary Energy Ratio i.e. the energy utilization rate of fuel) which can attain up to 95%, with very low noise pressure and gaseous emissions; so they could no doubt be considered as the state of art regarding electric efficiency for this power class. Nevertheless, they still have some drawbacks if compared to conventional electricity and heat supplies (like grid distribution and gas domestic burners/heaters), especially because of their high cost and their lower electric efficiency at partial loads. Still regarding this last aspect, the declared values are no doubt interesting for most of the applications (such as residential and small industrial

*E-mail address:* pietro.capaldi@cnr.it

http://dx.doi.org/10.1016/j.applthermaleng.2016.03.019
1359-4311/

**Nomenclature**

| | | | |
|---|---|---|---|
| I.C.E. | internal combustion engine (//) | $\eta_{E.E}$ | Powerplant electric efficiency (%) |
| P.E.R. | Primary Energy Ratio (%) | $\eta_{T.E}$ | thermal efficiency (%) |
| B.E.P. | Break Even Point (//) | $\eta_{G.E}$ | Engine Global efficiency (%) |
| b.m.e.p. | brake mean effective pressure (bar) | $\eta_{gen}$ | Electric efficiency of generator (%) |

purposes), but a higher electric efficiency, if available, could significantly make the application field wider, permitting a higher service factor and electric production in respect of a fixed heat demand by a generic utility. This additional electric power could also be strategic for battery storage in microgrids/smart grids or for the recharging of electric vehicles.

As regards innovative small cogeneration systems, designed to obtain a higher electric efficiency, no commercial examples have been found during the last years, as most of prototypes are based on the same similar schemes seen for the above mentioned models. In a previous paper [4] the author has showed that a better efficiency could be achieved with a high boosted down-sized internal combustion engine, coupled with a three-phase permanent magnet generator together with an inverter interface; owing to this, the system could be managed with a variable speed regulation, always at full load in order to keep the best efficiency (even for low and medium power ranges), so getting a clear advantage in terms of electric efficiency if compared to other machines. At the same time this philosophy showed some drawbacks, i.e. a very high cost for such a small plant (because of the high price of both rare-earth based generator and interface inverter) and reduced reliability especially in case of a long expected running life. For these reasons another solution should be individuated, which could be simpler in its architecture and characterized by a lower cost and a higher robustness: this choice was focused on an asynchronous generator which is no doubt a low-cost solution (not based on rare earths permanent magnets) and which doesn't need any expensive inverter for grid interface. Electric power production is based on I.C.E. torque variation at quasi constant speed, this involving a lower efficiency for both electric generator and engine, especially when a N.A. unit is adopted, because partial loads are obtained by throttling. On the contrary turbocharged units can give an important efficiency benefit for each different load at quasi fixed speed, with a better maximum power performance and a higher efficiency especially at partial loads thanks to a higher brake mean effective pressure and consequently mechanical output.

## 2. The downsizing philosophy applied to microcogeneration

The engine effectively adopted in the previous 20 kW electric powerplant [4] was the base for this new system designed to implement an asynchronous generator; this i.c.e. unit is derived from a mass produced automotive Diesel engine (Fiat 1.3 MultiJet), then converted into a stoichiometric spark ignition prototype by Istituto Motori and turbocharged with a single stage turbine. This engine represents one of the most advanced units today available on the market, owing to its four valve head with high turbulence cross-intake design, which are moved by a double overhead cams with hydraulic lifters and integrated rocker-arms. The combustion chamber (see Fig. 1) is placed inside the piston (Heron design) and was optimized to get a better performance at a quasi fixed rotational speed (≈1500 rpm). All these technical solutions led to an engine design very similar to large industrial units, which must be more robustly constructed (if compared to automotive units) to manage the pressure of a high boosted cycle. Also, these technical solutions could guarantee a longer expected life, in order to get an extended economical profit period.

One of the most important issues for this prototype was the selection of a new turbocharger which could better match the engine requirements for every load at a fixed speed of 1500 rpm, as the unit running conditions could result quite different compared to automotive application. In the microcogeneration unit [4] it was adopted the original Diesel engine turbocharger (Garrett GT 1241), but this choice limited both the maximum pressure and the operative range achievable by the engine. The reason was that the turbocharger was dimensioned for a higher intake and exhaust flow mass, owing to the lean operation of the Diesel cycle; also, it was designed to obtain a much higher engine power which involved a considerably superior air flow. So this unit resulted too large for the stoichiometric setting and for a low speed operation, being unsuitable to achieve a high efficiency (in terms of maximum pressure). Moreover, the operation of the same unit resulted too much close to the surge line, especially at partial load, causing some instability problems. So it was decided to analyze another different unit (Garrett GT 1238) designed for smaller displacement engines in order to compare it with the previous one. Furthermore, with the aim of getting a higher mean pressure and a better knock resistance, an intercooler was adopted for compressed air. As the microcogeneration system should be placed into a closed capsule it was not feasible the adoption of any conventional air to air unit; so it was adopted a prototype plate heat exchanger (water to air) modified to reduce the charging pressure drop, being also compact and easy to install inside the cogeneration unit. The cooling water temperature was set at 50 °C, which is the lowest operating value in most of district heating system as return water flow. In order to find an optimized configuration and setting among all these elements (engine, turbochargers and different heat exchangers) an analysis has been carried out by means of an engine simulation program (GT Power 7.3); in Fig. 2 the complete engine scheme is reported.

Thanks to the availability of the experimental efficiency maps, the above mentioned turbochargers (respectively Garrett GT1241 and GT 1238) were compared; in this way it was possible to find the different maximum torque values at W.O.T. (Whole Opening Throttle) for the two configurations without any intake pressure

**Fig. 1.** Four valve heads with central spark plug (right) and modified pistons with enlarged bowl (left).