Dynamic Modelling Of A Co-/Trigeneration System: The Advantages Of Simulation Over Experimentation

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Abstract. The aim of this work is to utilise simulation (rather than experimentation) as a tool to maximise the overall efficiency of a cogeneration system. The interest in small-scale, decentralized, cogeneration systems stems from the fact that they provide a promising alternative to conventional power generation. In cogeneration systems, the energy released through burning fuel is not only harnessed by enabling an engine to drive an electrical generator; furthermore, it utilises the thermal energy contained within the engine coolant, lubricant and exhaust gases to either provide heating, or to drive a vapour absorption refrigeration cycle for domestic or commercial building cooling. Given the complex interactions between cogeneration system components, dynamic simulations are required to evaluate the overall performance and identify critical aspects of system behaviour.

High-quality empirical data across performance parameters for cogeneration systems can be difficult to obtain. Continuously changing conditions such as temperature, pressure, gas velocity, fuel & air flow rates and ‘heat’ losses due to combustion, cannot be satisfactorily represented by static models. The high costs associated with purchasing and setting up system test rigs are also prohibitive. Instead, dynamic simulations provide more diverse information under varying scenarios enabling system performance prediction across economic, thermodynamic and operational boundaries.

In this work, we present a dynamic simulation based on a natural gas fuelled internal combustion engine used as the prime mover in a cogeneration system. The engine model is built with Gamma Technologies’ software platform GT-SUITE, which can realistically simulate internal combustion engine behaviour and performance. The remaining system components are modelled based on the 1st and 2nd law of thermodynamics in MATLAB/Simulink, from which the simulation will be driven. The final simulation model can be utilised to assess the performance of existing cogeneration systems, as well as analyse the effect of system modifications.

1. INTRODUCTION

In conventional power generation, a relatively small portion of the energy released through the combustion of fuel is used to generate electricity, while a larger portion is discharged as hot flue gases via the exhaust stack into the surrounding environment. This discharge represents destruction of exergy (or lost work). Cogeneration (combined heat and power) systems differ from conventional power generation systems in that they make use of this thermal energy which would otherwise be lost (Fig. 1). In a cogeneration unit, electricity and thermal energy are produced concurrently. A further advantage of cogeneration is that utilising energy in this way at the point of consumption also minimises transmission losses.

Figure 1: Schematic highlighting the efficiency and fuel consumption of (a) conventional power generation and (b) cogeneration; where $\eta_E$ electrical yield of an electrical power plant (production of electricity only), $\eta_Q$ yield of a boiler (production of heat only), $\alpha_E$ percentage of energy transformed into electricity in a cogeneration unit and $\alpha_Q$ percentage of energy transformed into usable heat in a cogeneration unit. (Adapted from Onovwiona & Ugursal, 2006).
In a “trigeneration” unit, electricity, thermal heating and cooling are produced concurrently. Both co- and trigeneration systems are suitable for both industry and household use. Small-scale residential co-/trigeneration systems could fully satisfy household energy needs by providing electricity, as well as space heating and cooling reaching fuel utilisation efficiencies of up to 70% to 90% (Fig. 1; Wu & Wang, 2006).

The idea behind small-scale residential cogeneration systems (Fig. 2) is rather than buying electricity from the grid and heating water for domestic use, both power and heat are provided by the cogeneration unit. Trigeneration systems augment the use of the available heat through a thermally-activated refrigeration system, as depicted in Fig. 3. However, to reliably meet both electrical and thermal demands, the operation of co-/trigeneration units in households is intermittent. This reduces the efficiency of the cogeneration systems considerably, due to both engine and system warm-up (transient system behaviour).

With increasing demand in space cooling, especially in a hot climate such as Australia, there is a rising interest in combined cooling, heating and power systems. However, with this relatively new technology, operation and control strategies have to be developed and optimised to obtain maximum efficiency (Weber et al., 2009; Angrisan et al., 2012).

2. PROBLEM DESCRIPTION

Again, due to multiple engine start-ups and shut-downs, overall system efficiency suffers compared to cogeneration units that operate in a stationary regime. Voorspools & D’haeseleeer (2002) have addressed the problematic, little understood, transient behaviour of the engine if operational control of the system involves frequent start-up and shut-downs of the engine. This is especially the case when the ‘rest periods’ of the engine last long enough for the engine to completely cool down.

Voorspools & D’haeseleeer (2002) showed experimentally that heat generation of a completely cold engine lags electricity production considerably. After a cold-start, the internal combustion engine takes approximately 5-10 minutes before it can produce appreciable heat and even then, the rate of heat generation is considerably less than at full power. It takes a period of 30 minutes from a cold-start, to yield 65% of the nominal power heat energy and up to one hour to reach 80% of the rate for constant operation. This is clearly a problem when waste heat is not only used for heating purposes but also for space cooling as the heat demands increase with trigeneration systems compared to cogeneration systems. Little research has been conducted in this area, especially in the context of trigeneration. In addition, a cold engine consumes distinctly more fuel than a warmed-up engine (Voorspools & d’Haeseleeer, 2002). The performance of both co- and trigeneration systems during start-up clearly needs to be improved.

Figure 2: Idealised view of an exemplary cogeneration unit (ZuhauseKraftwerk), front view (left) and rear view (right). (1) exhaust gas; (2) heater circuit 1 & 2; (3) fresh water; (4) hot water; (5) gas; (6) water storage tank connection; (7) control display; (8) communication and remote monitoring; (9) internal combustion engine; (10) generator; (11) vibration-reducing mounting foot; (12) heating circuit pump; (13) heat exchanger (primary-secondary circuit); (14) exhaust gas heat exchanger; (15) catalytic converter; (16) exhaust manifold; (17) heat exchanger; (18) secondary heating circuit pump. (Taken from Lichtblick, 2012).
3. BENEFIT OF SIMULATION OVER EMPIRICAL EXPERIMENTS

Considering the complex interactions of the various components of co-/trigeneration systems, dynamic simulations appear to be the best approach to evaluating overall performance and critical system behaviour (Alanne et al., 2009). In particular, the complex interactions between economic, thermodynamic and system-inherent relationships in co-/trigeneration systems make analytical solutions problematic. As such, disciplinary boundaries have to be crossed in the pursuit of improved overall efficiency of such complex systems.

3.1 Difficulty of obtaining empirical data

High-quality empirical data for cogeneration systems are often difficult to obtain. However, a greater range of performance parameters are available when using a simulation based on modelling (Fischer & Hoffmann, 2004). Fischer & Hoffmann (2004) therefore consider engine simulations superior to experimentally determined data. This is especially significant for a thermodynamic analysis, where engine characteristics (e.g. engine speed and power output) might be measured, but not directly related to the more important 'inner properties' such as entropy and heat fluxes (Fischer & Hoffmann, 2004). Static and quasi-static models cannot be used to examine changing conditions during the engine cycle. These changing conditions have a significant effect on temperature, pressure, gas velocity, fuel and air flow, heat transfer etc. Morel & Keribar (1990) made a strong case for utilising computer models, since heat transfer processes and the transient behaviour of engines are hard to determine experimentally.

3.2 Cost

The argument for preferring simulation over actual experiments due to the cost of accurate, suitable test benches was underlined by Samhaber et al. (2001). The high costs and efforts associated with purchasing and setting up test rigs were disproportionate to the findings thereby obtained. A wider range of different scenarios could be investigated using simulations. They also provide a much greater volume of information.

3.3 Flexible use and engine warm-up

Flexible use and engine warm-up are important challenges for improved cogeneration efficiencies. Cold-start experiments of actual engines are cumbersome and time-consuming, as long down times are required between runs to allow a sufficient degree of cooling (Rosato & Sibilio, 2013). Observations of combustion behaviour and characteristics are also limited by the number of sensors that can be employed and access to engine cylinders. Faster engine warm-up and improved, intelligent engine cooling systems would be beneficial to overall engine operations; again, simulation seems a reasonable strategy to investigate this (Boretti et al., 2008). While these findings were made from the automotive research perspective, the statements hold equally true for reciprocating engine-based co-/trigeneration systems, as thermal control of the engine is a major driving factor of any combined heat and power system.

Friction losses in the engine, resulting in increased fuel consumption, can be related to the engine temperature (Samhaber et al., 2001). During the early phase of engine operation, significant heat is absorbed by the engine components (around 60%), while approximately 30% of the thermal energy from combustion is transferred to the coolant and engine oil (Samhaber et al., 2001). Despite the added complexity, engine start-up and cool-down characteristics must be incorporated...
in any simulation aiming to determine optimal operational parameters (Chow & Wyszynski, 1999; Alanne et al., 2009; Rosato & Sibilio, 2013). Ferguson et al. (2009) emphasised the need to include start-up and cool-down behaviour of internal combustion engines in any simulation. Alanne et al. (2009) found that the initial warm-up period continued for the first 15 minutes after cold start, while the engine cool-down period was 25 minutes.

4. METHODOLOGY

4.1 Modelling framework

The prime mover of the present cogeneration system is a natural-gas fuelled, reciprocating piston, spark ignition, internal combustion engine. It is modelled in GT-SUITE (Fig. 4). The model includes the behaviour of the intake system, the cylinders, the combustion characteristics and the exhaust system. GT-SUITE also models heat transfer both to and from the engine. Some of the energy released during combustion is dissipated via the engine coolant circulating around the cylinders while some is lost to the engine lubricant (Fig. 5). Heat generated by friction is removed via the engine oil.

The thermal inertia of the engine as a whole, which includes the cylinder head, engine block and crankcase, are modelled as thermal masses which absorb energy by heat transfer during the early stages of engine operation, prior to the engine obtaining a steady-state, operational temperature. Extra accuracy is being obtained by modelling the engine’s internal pipework etc.

The remaining system components, such as the heat exchangers, the pumps, the thermal energy storage unit and the refrigeration system are all modelled in Simulink/MATLAB. To account for the various different types of heat exchangers and their respective design, the 1st law of thermodynamics provided suitable implementation in the case of the heat exchangers as the focus is on determining the temperature distribution (Shah & Sekulic, 2003). Similarly, the thermal storage system is modelled according to a heat rate or energy balance, which is a common approach (Wille-Haussmann et al., 2010; Dincer & Rosen, 2011).

The 1st law analysis is to be complemented by a 2nd law of thermodynamics guided approach (or exergy analysis). As early as 1980, Bejan (1980) made a strong case for the necessity of incorporating 2nd law analysis in a complete assessment of heat transfer equipment. Since then, this approach has developed into a standard method in the evaluation of cogeneration and trigeneration systems (e.g., Silveira & Tuna, 2003; 2004; Badami & Mura, 2010; Zare et al., 2012).

Figure 4: Detail view of the engine model map in GT-SUITE, depicting the intake system, cylinders, engine and exhaust ports.
4.2 Packages
GT-SUITE is a software platform from Gamma Technologies. It is capable of realistically simulating the behaviour of internal combustion engines and their performance. According to Gamma Technologies, “GT-POWER, part of the GT-SUITE, is the industry standard for engine simulations.” It was selected because of its ability to predict in-cylinder heat transfer. GT-SUITE has an extensive library of engine components that enable the user to build a complete engine model closely representing the overall engine. It is compatible with MATLAB and Simulink, making it possible to transfer simulated engine generated data from GT-SUITE to MATLAB/Simulink for further processing. The overall simulation is driven by Simulink, transmitting the control commands to GT-SUITE. GT-SUITE can also be used as a preparation tool for the conduction of experiments. The in-built ‘Design of Experiment’ function enables the user to identify the components of an engine where sensors should be placed. This is highly beneficial for model verification when actual system testing is performed.

4.3 Coupling
 Despite coupling blocks existing both in GT-SUITE and Simulink to enable data exchange and the simultaneous execution of the two independent, yet coupled, models, implementation was not easy. The GT-SUITE model is run and controlled from Simulink, which in turn acts as the clock for the simulation time steps to be taken by both models. Data generated in the GT-SUITE model is passed to Simulink where they get further processed and then passed back to GT-SUITE for consecutive time steps. Care had to be taken to account for the different numerical solvers and the respective point in time for the data exchange. This problem was further complicated by a mixture of implicit and explicit solution control employed for the different fluid circuits modelled in GT-SUITE. While the combustion process in the engine cylinders is solved using an explicit solution, the coolant and oil circuits utilise an implicit solver.

Allowing GT-SUITE to autonomously determine its own time steps considerably decreases the simulation time required. However, general accuracy diminishes, as the synchronisation between Simulink and GT-SUITE is not guaranteed anymore. To make up for this time offset, values previously passed on would either have to be held at a constant value until the next data exchange or be interpolated based on pre-defined values. It was therefore decided to force exact synchronisation between the two coupled models at the expense of computing time.

5. OUTCOMES
In its final state, with the incorporation of all components of the trigeneration system based on a 1st and 2nd law thermodynamic analysis, the simulation will enable a thorough investigation of the transient behaviour. The existing detrimental effect of a flexible usage pattern caused by unpredictable switching on and off of the trigeneration unit can be explored both on a qualitative as well as a quantitative level. Mechanisms for improving efficiency are far more suitably addressed in a simulation environment prior to exploring their potential benefit on a real system.

6. SUMMARY/CONCLUSION
We have argued here for the need for realistic simulations reflecting transient behaviour of co-/trigeneration systems. The general approach taken with model building is outlined. Initially, the system components (apart from the prime mover) are modelled using the 1st law of thermodynamics via heat rate/energy balances. A 2nd law of thermodynamics
analysis is then conducted to identify critical system behaviour in accordance with published literature in this field. The natural gas-fuelled internal combustion engine at the heart of the co-/trigeneration unit is modelled with the software package GT-SUITE, with the remaining system components built in Simulink/MATLAB. While coupling of the two different modelling platforms is possible and provided ‘out of the box’, the implementation is non-trivial. In the selection of time steps and numerical solvers, a balance has to be found between computing time and the accuracy of results. Ultimately, the proposed simulation model can be utilised to assess not only existing co-/trigeneration systems during their transient stages but also test novel control and operational procedures.

REFERENCES


