NRC Publications Archive Archives des publications du CNRC

Optimization and field demonstration of hybrid hydrogen generator / high efficiency furnace system

Entchev, E.; Manning, M. M.; Coyle, I.; Szadkowski, F.; Graydon, J.; Kirk, D.; Swinton, M. C.

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. /
La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version
acceptée du manuscrit ou la version de l'éditeur.

For the publisher's version, please access the DOI link below. / Pour consulter la version de l'éditeur, utilisez le lien
DOI ci-dessous.

Publisher's version / Version de l'éditeur:

<https://doi.org/10.1016/j.ijhydene.2008.07.073>

International Journal of Hydrogen Energy, 34, 10, pp. 4611-4616, 2009-05-01

NRC Publications Record / Notice d'Archives des publications de CNRC:

<https://nrc-publications.canada.ca/eng/view/object/?id=d1282e43-e5ac-4e14-8640-42433a19d81e>

<https://publications-cnrc.canada.ca/fra/voir/objet/?id=d1282e43-e5ac-4e14-8640-42433a19d81e>

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at

<https://nrc-publications.canada.ca/eng/copyright>

READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site

<https://publications-cnrc.canada.ca/fra/droits>

LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at

PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the
first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la
première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez
pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

<http://irc.nrc-cnrc.gc.ca>

Optimization and field demonstration of hybrid hydrogen generator / high efficiency furnace system

---

NRCC-51346

Entchev, E.; Manning, M.; Coyle, I.;
Szadkowski, F.; Graydon, J.; Kirk, D.; Swinton,
M.C.

May 2009

A version of this document is published in / Une version de ce document se trouve dans:
International Journal of Hydrogen Energy, 34, (10), pp. 4611-4616, DOI:
[10.1016/j.ijhydene.2008.07.073](http://dx.doi.org/10.1016/j.ijhydene.2008.07.073)

The material in this document is covered by the provisions of the Copyright Act, by Canadian laws, policies, regulations and international agreements. Such provisions serve to identify the information source and, in specific instances, to prohibit reproduction of materials without written permission. For more information visit <http://laws.justice.gc.ca/en/showtdm/cs/C-42>

Les renseignements dans ce document sont protégés par la Loi sur le droit d'auteur, par les lois, les politiques et les règlements du Canada et des accords internationaux. Ces dispositions permettent d'identifier la source de l'information et, dans certains cas, d'interdire la copie de documents sans permission écrite. Pour obtenir de plus amples renseignements : <http://lois.justice.gc.ca/fr/showtdm/cs/C-42>

National Research
Council Canada

Conseil national
de recherches Canada

Canada

Optimization and Field Demonstration of Hybrid Hydrogen Generator/ High Efficiency Furnace System

E. Entchev^{a*}, M. Manning^b, I. Coyle^a, F. Szadkowski^a, J. Graydon^c, D. Kirk^c, M. Swinton^b

^a CANMET Energy Technology Centre, Ottawa, Ontario, Canada

^b National Research Council Ottawa, Ontario, Canada

^c University of Toronto, Toronto, Ontario, Canada

Abstract

Hydrogen is seen as an energy carrier of the future and significant research on hydrogen generation, storage and utilization is accomplished around the world. However, an appropriate intermediate step before wide hydrogen introduction will be blending conventional fuels such as natural gas, oil or diesel with hydrogen and follow up combustion through conventional means. Due to changes in the combustion and flame characteristics of the system additional research is needed to access the limits and the impact of the fuel mix on the combustion systems performance. The hybrid system consists of a 5kW_{el} electrolyzer and a residential 15 kW_{th} high efficiency gas fired furnace. The electrolyzer was integrated with the furnace gas supply and set up to replace 5-25% of the furnace natural gas flow with hydrogen. A mean for proper mixing of hydrogen with natural gas was provided and a control system for safe system operation was developed. Prior to the start of the field trial the hybrid system was investigated in laboratory environment. It was subjected to a variety of steady state and cycling conditions and a detailed performance and optimization analysis was performed with a range of hydrogen/natural gas mixtures. The optimized system was then installed at the Canadian Centre for Housing Technologies (CCHT) Experimental research house. The energy performance of the hybrid system was compared to the energy performance of an identical high efficiency furnace in the Control research house next door.

Key Words: Hydrogen, Electrolyzer, Hybrid system, Furnace, Simulation, Combustion

Introduction

Hydrogen is seen as an energy carrier of the future and significant amount of research on hydrogen generation, storage and utilization is accomplished around the world. A number of new technologies utilizing hydrogen have emerged lately and most of them are near commercialization. However, an appropriate intermediate step before the wide acceptance of hydrogen would be blending conventional fuels such as natural gas, oil,

---

* Evgueniy Entchev, Canmet Energy Technology Centre, 1 Haanel Dr., Ottawa, Ontario, Canada K1A-1M1, tel:+613-992-2516, e-mail: entchev@nrcan.gc.ca

diesel, etc. with hydrogen. A hybrid hydrogen generator / gas fired furnace was developed and its performance was accessed in a residential application. The goal was to identify and mitigate the risks and potential changes in performance characteristics of the combustion appliances while they were fed with a variety of hydrogen/natural gas mixtures.

The project was executed in two phases as the first phase included a Hazard Operational Analysis (HAZOP) paper study followed by system installation and evaluation in laboratory environment. The electrolyzer was integrated with a residential high efficiency gas furnace and hybrid system performance was evaluated under a variety of typical steady-state and cycling conditions. The laboratory research included: mapping the hybrid system's performance while replacing up to 25% of natural gas flow with hydrogen, design and development of advanced control system for safe system operation and introduction of means for safe and effective hydrogen/natural gas mixing before combustion.

After completing the laboratory tests the hybrid system was installed and evaluated at the twin house facility of the Canadian Centre for Housing Technology. The objective was to gain data from the hybrid system performance while subjected to the “real life” environment and compare the performance to a conventional heating system.

Canadian Centre for Housing Technologies

Built in 1998, the Canadian Centre for Housing Technology (CCHT) (www.ccht-cctr.gc.ca) is jointly operated by National Research Council (NRC), Natural Resources Canada (NRCan), and Canada Mortgage and Housing Corporation (CMHC). CCHT's mission is to accelerate the development of new technologies and their acceptance in the marketplace.

The Canadian Centre for Housing Technology features twin research houses to evaluate the whole-house performance of new technologies in side-by-side testing Figure 1.

Figure 1 - CCHT Twin-House Facility - Control House (left) and Experimental House (right)

Table 1 - Twin House Characteristics

Feature	Details
Construction Standard	R-2000
Liveable Area	210 m ² (2260 ft ²), 2 storeys
Insulation	Attic: RSI 8.6, Walls: RSI 3.5, Rim joists: RSI 3.5
Basement	Poured concrete, full basement Floor: Concrete slab, no insulation Walls: RSI 3.5 in a framed wall. No vapour barrier.
Garage	Two-car, recessed into the floor plan; isolated control room in the garage
Exposed floor over the garage	RSI 4.4 with heated/cooled plenum air space between insulation and sub-floor.
Windows	Area: 35.0 m ² (377 ft ²) total, 16.2 m ² (174 ft ²) South Facing Double glazed, high solar heat gain coating on surface 3. Insulated spacer, argon filled, with argon concentration measured to 95%.
Air Barrier System	Exterior, taped fiberboard sheathing with laminated weather resistant barrier. Taped penetrations, including windows.
Airtightness	1.5 air changes per hour @ 50 Pa (1.0 lb/ft ²)
Furnishing	Unfurnished

The houses were designed and built by a local builder to the R-2000 standard. The houses feature a popular model currently on the market in the Ottawa region, and were built with the same crews and techniques normally used by the builder. The twin houses characteristics are presented in Table 1. The CCHT twin houses are fully instrumented and are unoccupied. To simulate the normal internal heat gains of lived-in houses, these houses feature identical ‘simulated occupancies’.

Methodology

The electrolyzer was evaluated using a side-by-side testing procedure. First, the twin houses were compared in identical configuration to establish a benchmark. Periods of benchmarking were spread throughout the heating season to establish consumption and temperature relationships between the two houses over a range of outdoor conditions. Following benchmarking, one house remained unchanged, referred to as the “Control House”, and the electrolyzer was connected to the furnace in the second house, the “Experimental House”. The differences between the operation of the Experimental House with and without the electrolyzer were then quantified, using the Control House as a reference. Following the experiment, the houses were returned to benchmarking conditions to ensure that no changes occurred to the house setup during testing.

Table 2 – CCHT Twin House Operating Conditions for the Benchmark and Experiment

	System	Description
1	Furnace	High efficiency gas condensing furnace with PSC motor provides high speed heating and low speed continuous circulation
2	Thermostat	Set point: 22°C, standard central location on main floor
3	Heat Recovery Ventilator (HRV)	Constant ventilation, 65 cfm 84% efficiency (nominal)
4	Window Shades	No exterior shades, All interior blinds down and horizontal
5	Simulated Occupancy	Standard Schedule
6	Humidifier	Off
8	Hot Water Heater	Standard Gas 81% efficiency (measured)

Hybrid System Set up

The system tested in CCHT consisted of HmaxCell^{TM}C5 electrolyzer and Olsen (GTH-50) high-efficiency condensing natural gas furnace integrated with check valves, pipes and flame arrester and allowed the two fuels to meet at a mixing section before entering the furnace. The set up of the hybrid system is shown in Figure 2.

Electrolyzer

The electrolyzer HmaxCell^{TM} C5 is capable of providing 1.8 litres per minute of hydrogen continuously and up to approximately 2.4 litres per minute for up to 20 minutes (capacity 0.11Nm³/h to 0.21 Nm³/h and standard purity of 99.7%). The power consumption ranges from 4.90 to 5.64 kWh/Nm³ and the distilled water feed rate is between 0.084 and 0.168 L/h. The electrolyzer stores hydrogen at up to 7.08 bar_g (708 kPa gauge). The supply is controlled by a needle valve and a regulator that reduces the pressure to approximately 0.25 bar_g (25 kPa gauge).

Furnace

The furnace used in the project was a conventional high-efficiency condensing natural gas furnace (Olsen model GTH-50). Its natural gas fuel input is specified as 14.65 kW and its output 13.63 kW, which represents an efficiency of 93%. At heating mode, the blower supplies 39.86 m³/min of air to the house. At continuous circulation mode of operation it supplies 23.35 m³/min of air. Electrical signals were sensed from the gas valve's electronics to provide automatic control of the hydrogen supply. The furnace start-up sequence begins with pre-purge operation of the combustion air blower, followed by hot surface igniter activation, gas valve operation (and ignition of the gas) and finally operation of the circulating blower that moves the air in the building heating system. On

shutdown, the fuel supply is ended, then the combustion air blower shuts down after a delay to carry out post-purging and lastly the building air circulation blower shuts down.

Figure 2 - Hybrid system in the Experimental house at CCHT

Natural Gas and Hydrogen Supply

Natural gas was supplied from the regular residential gas line. It was fitted with a ball shut-off valve and a check valve to prevent any possible back-flow of hydrogen. It then joined the hydrogen supply. Natural gas used had a heating value 37.44 MJ/m^3 HHV (101.325 kPa , 15°C) and the gas pressure was 1.7 kPa gauge ($7''\text{H}_2\text{O}$). The hydrogen supplied to the furnace was at a pressure of 20.67 kPa (gauge) to 34.47 kPa (gauge) with a volumetric flow rate of 2.08 L/min . The hydrogen supply to the furnace follows a line that led to the following devices: an electrically operated solenoid valve, a backcheck valve and a flame arrester. It then met the natural gas supply in a "T" junction contained a metal helix to promote better natural gas/hydrogen gas mixing. The natural gas/hydrogen gas blend then entered the furnace combustion system in conventional fashion.

Control Logic

The electrically-operated valve that controlled the hydrogen supply to the furnace was opened by a logic circuit that executed "and" control logic: all conditions have to be met for the valve to open. The first condition was a position of the switch that enabled the operator of the system to control the hydrogen input. If this switch was closed, two further conditions had to be met: The "smart valve" that controls the gas supply to the furnace must be open, and the circulating blower motor for the building air must be

running. When all these conditions were met, there was an adjustable time delay before the hydrogen valve was opened. The operator's switch was left in the "on" position during furnace cycles, with the net effect of the hydrogen line turning on shortly after the entire furnace start up process was complete, and turning off immediately as the shutdown process began.

Results

The efficiency of the Control House's furnace was 93.3%. The calculated efficiency of the Experimental House's furnace was 92.7% while burning natural gas and 93.2% when burning blended 7%vol hydrogen and natural gas fuel. These calculations revealed a slight increase of 0.5% efficiency when the hydrogen was supplemented. The hydrogen accounted for 3.2% of the higher heating value (HHV) of the fuel that was burned during the testing. The heat output of the furnace decreased by 2% when the hydrogen was introduced due to the lower heating value of hydrogen (12.08MJ/m^3) compared to the natural gas (37.44MJ/m^3). Two tests in the Experimental House were done sequentially, first without and then with hydrogen. The test with hydrogen added led to slightly higher flue gas and combustion air temperatures. The temperature per kW increased from 1.99 without hydrogen to 2.18 with hydrogen while it was 2.16degree/kW in the Control House. The furnace condensation in the Control House was 13.5% lower with decreased natural gas flow. The difference in the furnace efficiency in the Experimental House with and without hydrogen was 0.5%, which is directly related to the reduced amount of condensation collected during the efficiency tests.

The excess air calculation shows similar values of 81% for the two furnaces when burning natural gas. The excess air increases to 84% with the addition of hydrogen, since less oxygen is required to burn hydrogen compared to natural gas. The measured CO_2 emissions decreased by 7% when the hydrogen was added to the fuel, which is a direct consequence of 7% less natural gas being burned.

The daily electrical consumption of the Experimental House furnace is an indication of the auxiliary energy use Figure 3. If the houses are completely identical, the benchmark trend line should have a perfect slope of 1 and an intercept of 0. The actual benchmarking trend line, plotted in blue, comes very close to this ideal: with a slope of 0.995 and intercept of 0.064. A similar trend is seen by the electrolyzer data, plotted in pink. The slope of the experiment trend line is 1.018, with an intercept of -0.133 . A similarity between the two trend lines indicates that although the Experimental House furnace was being supplemented by hydrogen, its electrical consumption remained similar to the benchmark condition. This is also an indication that the furnace spent a similar amount of time in heating mode with and without the hydrogen supplement from the electrolyzer.

In the Experimental House, the total heating system electrical consumption is a sum of furnace and electrolyzer electrical consumption.

Figure 3 - Heating System Electrical Consumption

During the experiment, the added electrical consumption from the electrolyzer ranged from 2.12 kWh/day to 5.12 kWh/day, with an average of 3.37 kWh/day. A decrease in daily furnace natural gas consumption was recorded, as a result of the supplement of hydrogen from the electrolyzer. This decrease occurred across the full range of experiment conditions, ranging from 9.9 to 13.0 MJ of savings per day. The average decrease in natural gas consumption was 11.0 MJ/day over the testing period. At low heating loads, the benchmark system and hybrid system trends are similar: the savings in gas consumption being made up for almost exactly by the increased electrolyzer electrical consumption. The two trend lines begin to diverge at high heating demands, the hybrid energy system setup requiring more total energy than the benchmark at high heating loads.

The natural gas consumption, electrical consumption and total energy consumption trends were used to estimate the savings and consumption increases of the hybrid system over full range of average outdoor temperatures. Over the 10°C to -25°C outdoor temperature range, gas savings can be expected to increase from 10.2 MJ/day to 17.3 MJ/day. Added electrical consumption grows with the increased demand for hydrogen gas, rising from 2.37 kWh/day to 10.41 kWh/day as the outdoor temperature is decreased. The net result is an increase in total heating consumption for temperatures at and below 5°C. The net increase is the highest on the coldest day of the analysis, -25°C, when the electrolyzer would be expected to cause the Experimental House heating system to consume an additional 22 MJ/day.

Given the daily average temperatures for a typical heating season in Ottawa (2002-2003), the temperature-consumption relationships can be applied to predict the total seasonal consumption and savings. During this season, it is predicted that the Experimental House with high efficiency furnace would consume approximately 2154 kWh of electricity, and 51692 MJ of natural gas. The use of the electrolyzer would add approximately 1132 kWh of electrical consumption, while saving approximately 2753 MJ of natural gas.

Economic Analysis

Over the test period, the use of the electrolyzer resulted in an average daily reduction in furnace natural gas consumption of 11.0 MJ/day. The electricity required to produce the hydrogen added to the total heating system electrical consumption, consuming on average an additional 3.4 kWh/day. While this results in a net increase in heating energy consumption of 1.2 MJ/day, at current gas and electricity prices the increase in cost is approximately 6.5 cents/day. The trends developed during the experiment indicate that as the heating load increases with colder weather, the daily natural gas savings and the electrolyzer electrical consumption both increase. For a cold day with an average outdoor temperature of -25°C , the trends predict a natural gas savings of 17.3 MJ/day, and an increased heating system electrical consumption of 10.4 kWh/day. The net increase in heating energy consumption would be approximately 20 MJ/day, with a net increase in heating costs of 35.8 cents/day at current prices. Cold weather testing is required to confirm these predictions.

To better illustrate the economic analysis of the hybrid electrolyzer-furnace system, Figure 4 compares the electricity prices required at varying outdoor temperatures to make the system favourable. This comparison was done using the current natural gas price of $0.35 \text{ \$/m}^3$. These calculations show that the coldest outdoor temperatures, when the most electricity is required, would need the price of electricity to drop to $0.016 \text{ \$/kWh}$ for economic favourability. At 10°C , the electricity prices need only drop to $0.04 \text{ \$/kWh}$ to favour the hybrid electrolyzer-furnace system. Seasonal calculations were performed to predict the added electrical consumption and resultant gas savings of operating the Experimental House furnace with the electrolyzer. These calculations revealed that an additional 1132 kWh of electricity would be required to produce 2753 MJ of gas savings during the 2002-2003 Ottawa heating season. At current gas and electrical prices, the added seasonal cost of operating the system would be $\$30.86$.

The same relationship can be used to identify the conditions for profitability. In order for the electrolyzer running in the test configuration to provide an overall profit during the heating season in the CCHT Experimental House, the cost of gas (in $\text{\$/m}^3$) must be greater than 15.4 times the price of electricity (in $\text{\$/kWh}$). Figure illustrates this relationship.

Figure 4 - Break even electricity prices using the current cost of natural gas

Figure 5 - Cost analysis for the operation of the electrolyzer in the CCHT Experimental House during a typical heating season

Conclusions

A hybrid furnace-electrolyzer energy system was successfully installed and tested at the CCHT Experimental House. A hydrogen generator incorporating an inexpensive stack was integrated with and fed hydrogen to a high efficiency furnace replacing 9% of the natural gas fuel. During the testing period the hybrid system was able to meet and to satisfy house space heating demands. The electrolyzer emitted waste heat that was circulated throughout the house and assisted in meeting its thermal load. Since the furnace on time per cycle was still higher than the one in Control House, the radiative heat was not enough to compensate for the decreased heating value of adding hydrogen to the natural gas fuel. During the testing period the electrolyzer produced an average savings of 11.0 MJ/day in furnace natural gas consumption, and an average increase of 3.37 kWh/day in heating system electrical consumption. Savings in gas consumption were highest on the days with the largest space heating demand. Added electrical consumption was also highest on these days, due to the increased electrolyzer operation to meet the heating demand. Average daily outdoor temperatures during the experiment were typical of spring conditions, ranging from -2.7°C to 12.7°C . Results were extrapolated to predict the system operation during extreme cold winter conditions. At an average outdoor temperature of -25°C , it is predicted that operating the furnace with the electrolyzer will save approximately 17.3 MJ of natural gas per day. Electrolyzer operation will require an additional 10.4 kWh/day of electricity on top of the normal furnace electrical demands. The net result would be an increase in the overall heating system consumption of approximately 22 MJ/day.

Acknowledgements

The project team would like to acknowledge the contribution of Canadian Program for Energy Research and Development (PERD) for the financial support throughout the project.

References

1. Entchev E., M. Manning, I Coyle, F. Szadkowski, Performance Evaluation of a Hybrid Electolizer/High Efficiency Furnace System, Final report NRCan- 00234-EE, 98, 2007.
2. National Energy Board “Canada’s Energy Future: scenarios for supply and demand to 2025” Canada, July 2005.
3. Entchev, E., Swinton M., Gusdorf J., Szadkowski F, Manning M. Demonstration of the first SOFC in Residential Application”, Final report CETC – EE2001, Ottawa, Canada, October 2002.

4. Swinton, M.C.; Moussa, H.; Marchand, R.G. "Commissioning twin houses for assessing the performance of energy conserving technologies" (NRCC-44995), Clearwater, Florida, December 2001.