NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Combined Cooling, Heating, and Power (CCHP) System

Cooperative Research and Development Final Report

CRADA Number: CRD-14-570

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CRADA Report
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Cooperative Research and Development Final Report

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the final CRADA report, including a list of subject inventions, to be forwarded to the DOE Office of Science and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: Be Power Tech, Inc.

CRADA number: CRD-14-570

CRADA Title: Combined Cooling, Heating, and Power (CCHP) System

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$ 79,326.00
TOTALS	$ 79,326.00

Abstract of CRADA Work:

NREL and Be Power Tech, Inc. (Be Power) will jointly develop a new combined cooling, heating, and power (CCHP) system that uses desiccants in combination with evaporative cooling and fuel cells. The combined system will have better economics and business case than a separate desiccant enhanced air conditioner and fuel cell system. The overall system is expected to become a net revenue generator by delivering power and air conditioning to a building while inputting natural gas and water. This development effort will revolve around adapting NREL's desiccant cooling technology to work with Be Power's proprietary system integration design for CCHP systems. The objective of the CRADA is to develop, then commercialize this CCHP system by jointly developing the system integration design, testing methods, and hardware for this system. The commercial name given to the CCHP system is BeCool™.

Summary of Research Results:

This report contains protected CRADA information, which was produced under CRADA No. CRD-16-570 and is not to be further disclosed for a period of five (5) years from the date it was produced except as expressly provided for in the CRADA.

NREL provided expert consultation and design assistance to implement NREL's desiccant cooling technology into the CCHP system. The tasks were to co-develop a CCHP system using NREL's design tools and expertise. The project was structured into four project areas based on NREL areas of support for Be Power Tech:

1. Detailed system modeling

NREL and BePower Tech engineers worked together to develop two heat and mass exchanger designs that are a part of the air conditioning system:

- A plate and frame membrane based dehumidifier that uses desiccant, water and a sweep air stream to cool and dehumidify a process air stream (HMX2)
- An indirect evaporative cooler that accepts the dehumidified process air and cools it down to the desired delivery temperature (HMX3).

NREL performed thermodynamic modeling using the geometrical inputs provided by BePower Tech to predict performance and provide feedback on how to improve the system's design. The design assistance is described in section 2. This intelligence provided BePower Tech the ability to construct two systems:

- A 1.5 ton prototype air conditioning sub-system used to inform the design of an integrated CCHP system
- A 5 ton proof of concept CCHP system built to demonstrate the functionality and energy savings.

Figure 1 below shows the general process of the CCHP system co-designed by Be Power Tech and NREL. The fuel cell and regenerator system is combined with NREL's evaporative liquid desiccant air conditioning concept (ELD-AC). In the diagram, process air is dried with HMX2 (dehumidifier) and sensibly cooled with HMX3 (indirect evaporative cooler). Liquid desiccant is regenerated by the combined fuel cell and regenerator, which provides the HMXs with concentrated liquid desiccant and water.

Oak Ridge National Laboratory tested the 5 ton system as a verification step of its performance[1]. The measured performance showed the CCHP system to be a promising technology that can save energy and reduce the impact of air conditioning on the electric grid.

[1] D. Betts, M. Ally, S. Mudiraj, M. Tilghman, M. Graham (2017). *Oak Ridge National Laboratory Small Business Voucher CRADA Report: Natural Gas Powered HVAC System for Commercial and Residential Buildings*. ORNL/TM-2017/211.

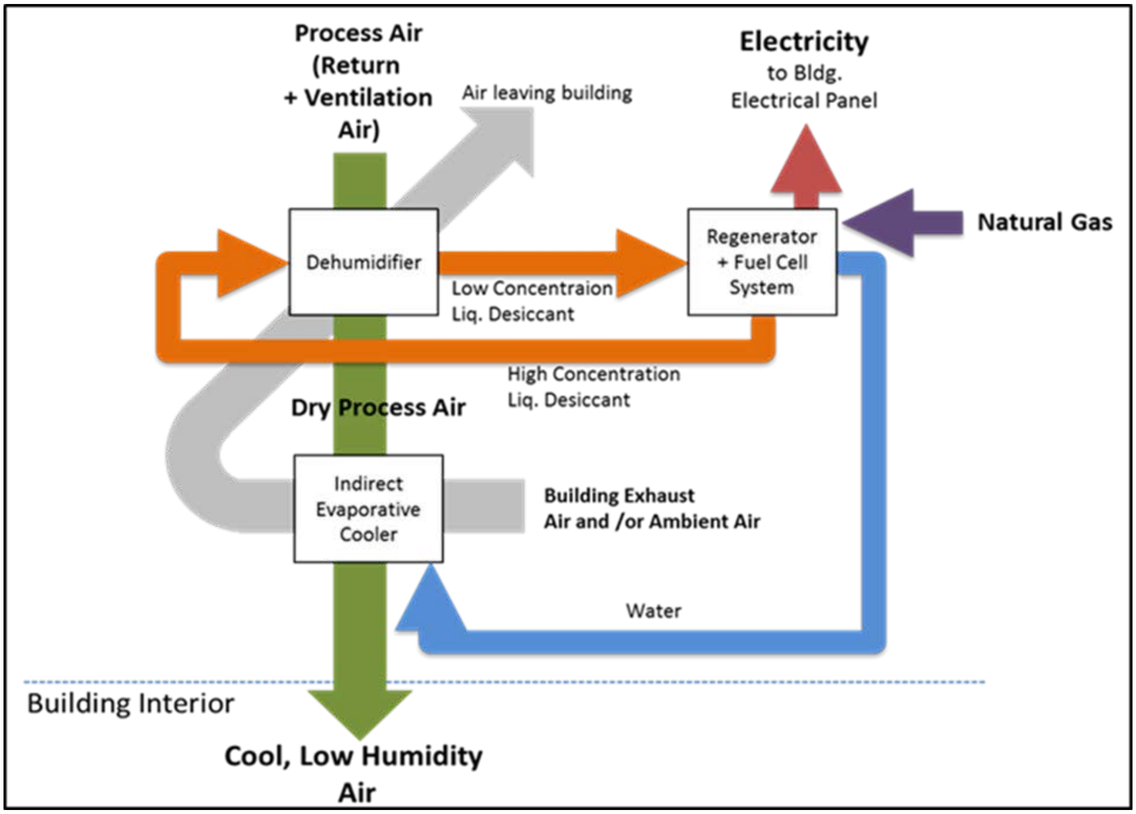

Figure 1. System diagram of proposed Be Power CCHP system.

2. Heat and Mass Exchanger (HMX) design support

NREL used our existing heat and mass exchanger models from work performed in 2010-2013[2,3] and used geometrical inputs from BePower Tech's designs to determine performance. NREL then provided feedback to improve heat and mass exchanger design, which were incorpotated into BePower Tech's designs. These designs were then implemented in the 1.5 and 5 ton systems described in project area 1 above.

The heat and mass exchanger models for the dehumidifier (HMX2) and sensible evaporative cooler (HMX3) were used in a reverse-design process. Initial performance was determined and model inputs were:

- Inlet air (30% outdoor air / 70% return air): 27.7°C dry bulb, 18.4°C dewpoint
- Outlet air: 15°C dry bulb, 10°C dewpoint
- 1 ton (3.5 kW) of cooling.

[2] E. Kozubal, J. Woods, R. Judkoff 2012. *Development and Analysis of Desiccant Enhanced Evaporative Air Conditioner Prototype.* NREL/TP-5500-54755.
[3] J. Woods, E. Kozubal 2013. *Desiccant-Enhanced Evaporative Air Conditioner: Numerical Model and Experiments* NREL/JA-5500-56533. Energy Conversion and Management Vol. 65 January 2013 pp. 208-220.

The model was then used to determine performance parametrics to find the design space. For HMX2 (Figure 2), The model inputs were the layer thickness and thermodynamic quantities (e.g. conductivity, vapor pressure, and water diffusivity):

- Plastic plate (2 plates per channel pair)
- Membrane (2 membranes per channel pair)
- Desiccant film (2 per channel pair)
- Water film (2 per channel pair)
- Process side air gap
- Exhaust side air gap.

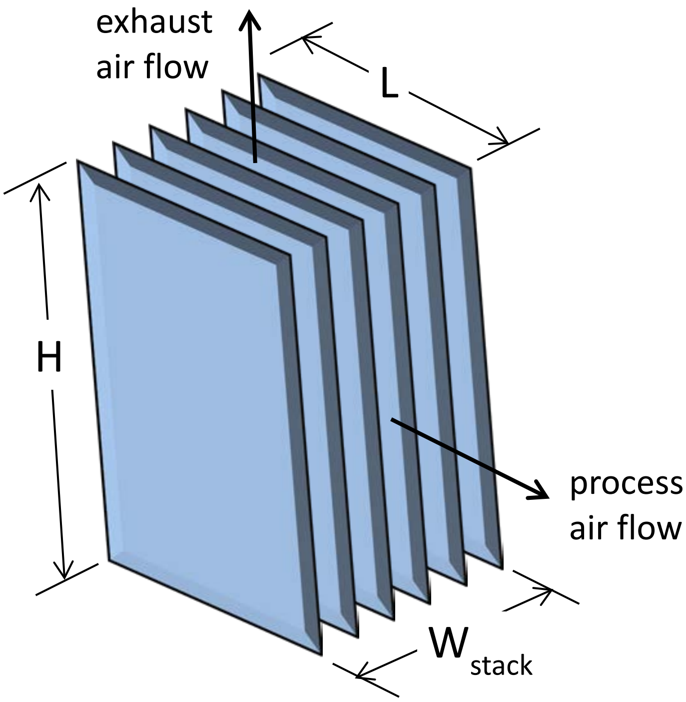

Figure 2. Depiction of the dehumidifier process and exhaust air flows as they pass through the parallel plate stack (HMX2).

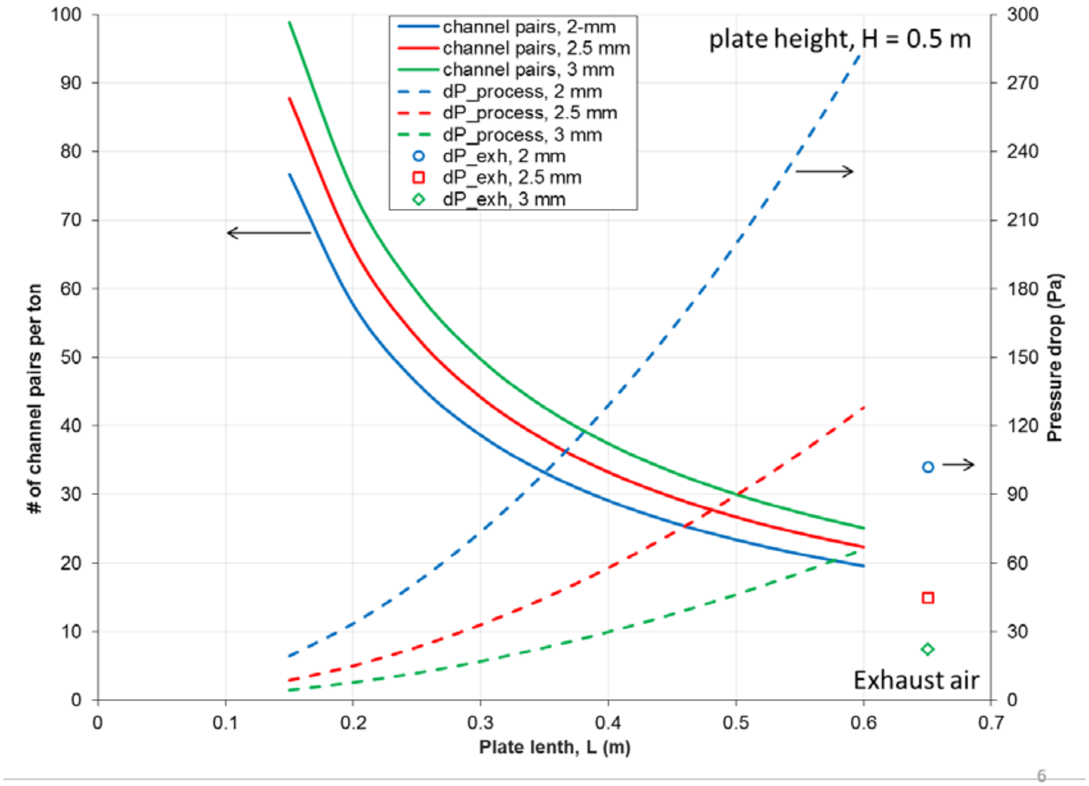

Figure 3. Shows and example of the trade-off of channel gap thickness, length and height vs the resultant air side pressure drop and number of channel pairs for HMX2.

The information shown in Figure 3 provided the design engineers with the necessary intelligence to choose a form factor for both efficiency and manufacturing considerations.

For HMX3, a similar design approach was used. Simulations were run using the following inputs:

- Vary process-side gap width between 2.3 and 3.1 mm
- Fix pressure drop at four levels
- Two exhaust-side gaps (1.5 & 2 mm)
- Fix wet-bulb effectiveness at 120%
- Solve for:
  - Number of channel pairs required
  - Plate length required
  - Stack-up width

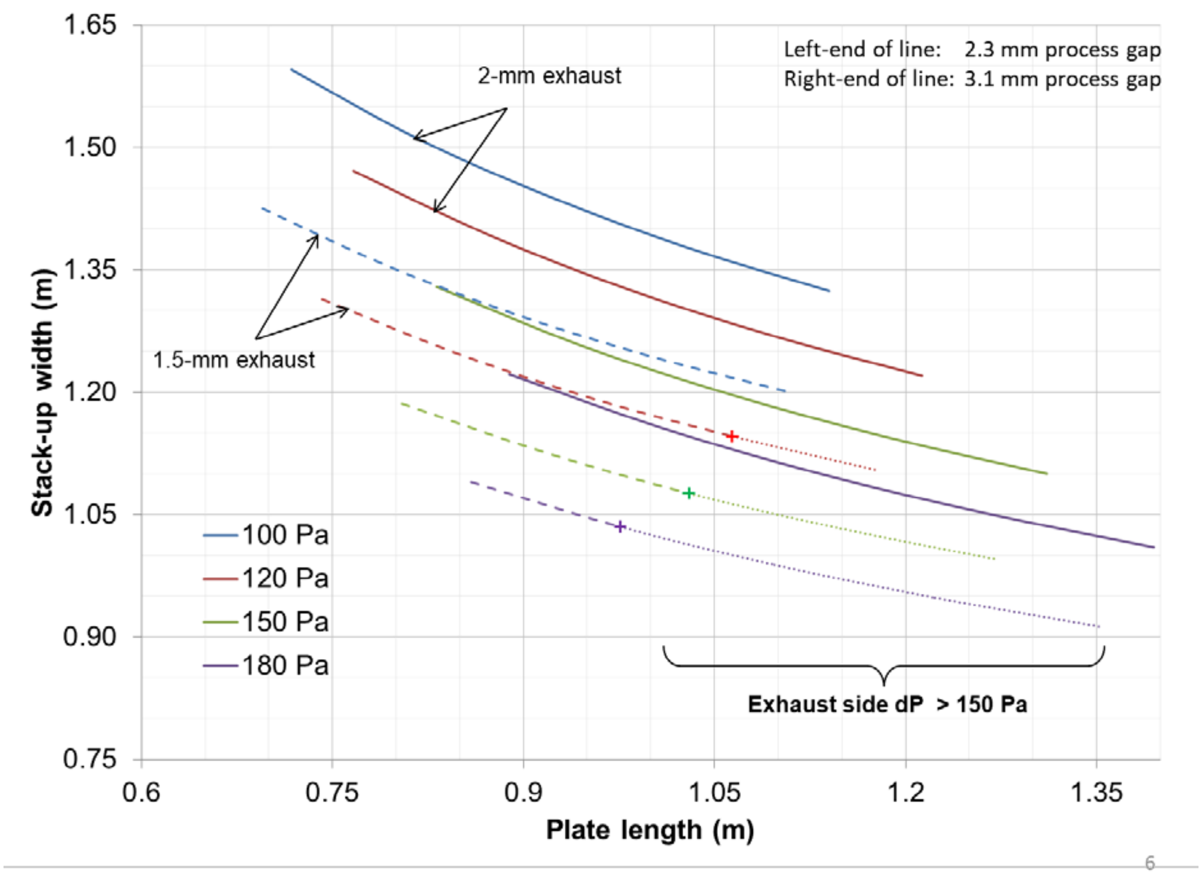

Figure 4. Example of HMX3 stack up width as a function of pressure drop, exhaust air and process air channel gaps.

The information shown in Figure 4 provided the design engineers with the necessary intelligence to choose a form factor for both efficiency and manufacturing considerations. From inspection of the graph, the engineers are able to easily see the trade-offs between air gaps sizes, air-side pressure drop, HMX plate length and width. Table 1 shows the specific case studies provided to the design engineers given their feedback on HMX2 manufacturing constraints.

Table 1. HMX2 air gaps, length, height and width study.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	
Channel pairs	140	140	140	136	142	134	
Stack width	48	48	48	48	48	48	inches
Plate height	38	38	38	38	38	38	Inches
Plate length	20	20	20	20	20	24	inches
Spacer	3-3 dots	4-3 dots	3-3 dots	3-3 dots	3-3 dots	3-3 dots	
Exhaust flow rate	1400	1400	1200	1400	1400	1400	CFM
Exhaust channel gap	3	3	3	3.25	3.12	3.25	mm
Process channel gap	3.12	3.12	3.12	3.12	2.9	3.25	mm
Supply dewpoint	10.26	10.26	10.44	10.42	10	9.69	C
ΔP_process	74	82	74	78	90	85	Pa
ΔP_exhaust	177	197	140	147	152	105	Pa

3. **HMX characterization.**

   The project concluded prior to funding this activity. No work was done for this activity.

4. **Technology impact analysis. Be Power Tech will work with NREL to estimate the environmental, grid stability improvement, cost reduction, and energy independence benefits of the BeCool™ system.**

   The project concluded prior to funding this activity. No work was done for this activity.

Subject Inventions Listing:

None

ROI #:

None

Report Date:

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DOE Program Office:

Buildings Technologies Office, Fuel Cell Technologies Office

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