The Development of a Binary Fluid Ejector (BFE) Thermally Driven Refrigeration System

Final Outcomes Report

By
May-Ruben Technologies, Inc.

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1. Executive Summary

May-Ruben Technologies (MRT) entered into a CCEMC supported research project in 2011 to develop and demonstrate a novel, thermally driven binary fluid ejector (BFE). MRT's patented technology is based on use of a fluidic, rather than mechanical compressor to provide the refrigerant entrainment and compression for a space cooling system. The conventional electric motor is replaced by a boiler which provides the drive energy and the mechanical compressor is replaced by a gas phase fluidic compressor called an ejector.

Project Objectives

The objective of the CCEMC supported project was to:

- develop governing equations to describe a binary fluid ejector,
- incorporate these into a Computational Fluid Dynamic (CFD) computer model,
- build a test rig to empirically validate the model's ability to predict results,
- use the model to study the relative impact of various fluid properties on efficiency
- use the indicated key properties to build an algorithm to search chemical databases to identify potential binary fluid candidates
- build a lab scale test rig to demonstrate the COP (coefficient of performance) of a selected fluid under operating conditions
- use the indicated performance to assess the commercial viability of BFE in selected applications.

Each of these work steps was successfully completed. At the end of this CCEMC sponsored research project, MRT was able to empirically demonstrate that a Binary Fluid Ejector using benign fluids supplied by Chemours (formerly DuPont) can produce nearly a 300% improvement over the prior art of single fluid (water) steam ejector refrigeration systems used for space cooling conditions. Such improvements in performance, together with the lower capital cost and greater operating reliability, should make waste heat driven ejector based refrigeration cycles a viable, cost effective commercial technology.

Potential Impact on GHG Emissions

This trend to distributed generation through cogeneration or Combined Heat and Power (CHP) devices that capture and use the waste heat from the electrical generating component will benefit society through more efficient, less polluting energy production. These units typically have an 85% overall efficiency when they are able to use the harvested waste heat. Unfortunately, commercial buildings need cooling more than they need heating. Based on the projected cost/benefit analysis contained in this report, there is a solid opportunity for BFE to use the waste heat generated from a CHP unit for space cooling. This would increase the year round efficiency of the units. By improving the economic return for a CHP unit, BFE would contribute to GHG reduction on an indirect basis by acting as a catalyst to further incent the deployment of CHP units. On a direct basis, BFE will reduce the amount of electrical demand required for space cooling. The impact on GHG reduction from offset electricity varies by region, but using the guideline numbers from Sustainable Development Technology Corporation (SDTC), it is possible to calculate the GHG reduction for Canada and for Rest of World from a deployment of BFE CHP units.

If, at market maturity, a BFE cooling system is installed in 1% of the prime categories of commercial buildings, then the offset of electrical power for cooling would result in a reduction in GHG emissions for North America of 4.3 million tonnes per year. Today, 9% of the electricity in the U.S. is produced from CHP. If the same penetration were obtained for commercial buildings, the North American reduction in GHG would be 40 million tonnes per year, with a global potential of over three times that amount.

New IP Developed During the Project

During the completion of this project, MRT was able to hire and develop a team of highly qualified personnel. On average, the company had four Phd's engaged in research, all recent graduates in mechanical engineering from the University of Calgary. Through literature research, analysis, and empirical testing, they developed world leading knowledge and insight into the thermal and fluid dynamics of ejector refrigeration. MRT has been granted a Canadian patent for a new class of ejector, termed a binary fluid ejector. In addition to this very broad patent, the company has developed further IP which may be patentable in the following areas:

- The impact of fluid properties on overall ejector refrigeration efficiency. Two of the four properties used by MRT for fluid selection has not previously been researched.
- A unique design of the ejector nozzle versus the conventional concentric nozzle. This enhances performance.
- Unique design features within the ejector body to improve fluid dynamics when dealing with higher back pressures from the condenser.
- Design for a fractionating condenser system that allows low pressure in the first stage of the condenser, which promotes ejector efficiency, while at the same time allowing engineering control to generate high pressure in the second stage of the condenser, which promotes effective heat rejection even on hotter days.

Next Steps toward Commercialization

MRT has identified the addition of adding a waste heat driven BFE space cooling component to cogeneration (CHP) devices as the best market entry. The ability to cost effectively use the waste heat from a cogeneration unit to provide space cooling would be of great benefit but today there is no cost effective integrated device to provide heating, cooling, and power. Because absorption chillers are generally uneconomical, there is a tremendous need in the marketplace for thermally driven space cooling.

Though there is further research and development required to develop a commercial product, that effort is underway. MRT is working with a strong collaboration team, Gas Technology Institute, Chemours (formerly DuPont), and Ecologix Heating Technologies, Inc., an Ontario manufacturer of electric heat pumps and air handlers. The first step to commercialization is to build a 2 RT lab scale prototype BFE cooling system that will demonstrate the fractionating condenser design developed by MRT and GTI, using fluids supplied by Chemours. The next step will be fabrication of a 20 RT beta commercial prototype. MRT has secured one source of funding to assist in this effort and will be seeking further funding in 2016.

Although there is still much work to be done in developing and using this new tool called BFE, it is a promising next chapter. There are other opportunities beyond space cooling. The BFE thermally driven refrigeration cycle is a platform technology with the potential for transformational impact on energy use patterns in various sectors. It can be configured to provide residential and commercial space heating/cooling and water heating, industrial process heating/cooling, industrial distillation and drying, and water desalination or remediation. The support of CCEMC in the infancy of this technology was instrumental in getting to this point. That support may bear fruit in ways not even yet foreseen.

2. PROJECT DESCRIPTION

a) Introduction & Background

The primary goal of this research and development project was to demonstrate the technical merits of the BFE concept. Through the uses of advanced analytical and numerical research tools, including Computational Fluid Dynamic modeling (CFD), the West-Grid supper computer (Western Canada Research Grid), advanced 3D metal printing (jet nozzles), proprietary algorithms for binary fluid search and performance assessments, two state-of-the-art fully instrumented test rigs, collaboration with the University of Calgary, 3M Corporation, and DuPont, extensive ejector research literature review, access to the NIST fluid database (US), and a team of in-house scientists with expertise in fluid mechanics, thermal dynamics, fluid material properties, and physics, MRT has empirically demonstrated a 300% improvement in COP (over that of a single-fluid ejector: steam), using a binary fluid pair supplied by DuPont in a physical test rig operating with a binary fluid ejector (BFE) specifically designed to process two chemically distinct working fluids. The operating conditions for these performance tests were similar to space cooling applications (air conditioning).

Gas phase ejectors are fluidic devices that accomplish compression of a secondary gas (the refrigerant), by action of an expanding primary gas (the drive fluid). The secondary fluid absorbs heat at low temperature from an evaporator, similar to refrigeration and heat pump processes, evaporators associated with distillation processes such as distilling water or desalination, or desiccation processes used for drying applications such as gravel, paper, grain, etc. The primary drive gas is produced in a boiler under high pressure. This high pressure gas expands through a supersonic jet nozzle within the body of the ejector, which is responsible for compressing the secondary refrigerant gas. The primary fluid absorbs heat at high or moderately high temperatures from a waste heat source, such as electric generation turbines or engines in CHP systems, burning a fuel such as natural gas or propane, solar energy, etc. A complete system includes a condenser that returns the working fluid to liquid phase by rejecting heat to ambient air, cooling tower water, or some other source of cooling fluid, separates the binary fluids, and returns the primary drive liquid back to the boiler and the secondary refrigerant liquid back to the evaporator to complete the cycle.

Gas phase ejectors have been in use for over 100 years for the purpose of cooling air or water, for heating air or water (heat pump), for distillation processes such as the concentration of fruit juices, and various process cooling applications. Traditional ejector systems employ a single fluid, usually water/steam. By contrast, the Binary Fluid Ejector (BFE) uses two chemically distinct fluids, one optimized as the primary drive fluid for the <u>forward</u> Rankine half of the thermal cycle, i.e. the boiler, jet nozzle, and condenser, and the other one optimized as the secondary refrigerant fluid for the <u>reverse</u> Rankine half of the thermal cycle, i.e. the evaporator, ejector body, and condenser. The two chemically distinct fluids are therefore referred to as a binary fluid pair. The advantage of using two chemically distinct fluids as opposed to a single fluid is that the binary fluids can be individually optimized, one for duty as an efficient refrigerant, and the other for duty as an efficient drive fluid (the compressing fluid).

b) Project Goals

The primary goal of this project was to physically demonstrate the technical merit, and to empirically measure the performance in terms of COP, of a Binary Fluid Ejector operating with an actual boiler, evaporator, and condenser in a fully instrumented test system. The original project application was distillation, which can be applied to treat process or polluted water, desalination of brackish or sea water, petrochemical distillation, pharmaceutical processes, and others. This application was originally chosen because the thermal cycle for distillation allows complete engineering control over the temperature of the boiler, evaporator, and condenser. This application goal was changed at mid-course to space cooling (building air conditioning) because industry support for distillation was found to be weak. Industry support for gas or waste-heat driven BFE space cooling applications was successfully developed, and included the 3M Corporation (Canada & US), E. I. du Pont de Nemours (DuPont US), the Gas Technology Institute (US), and Ecologix Heating Technologies Inc. (Cambridge, Ontario).

The supporting goals for the BFE performance demonstration were numerous, and are listed below in rough project chronology order. All of these goals were accomplished during the course of the project. Some supporting goals were dependent on information from previous goals, some overlap with respect to development and validation, and some were ongoing and evolutionary in nature.

1. Extensive research and literature review to establish baseline ejector performance for single fluid operation (water steam), as well as for traditional ejector geometry and fluid dynamic behavior.
2. The development and validation of computer simulation tools, principally CFD modeling, required to investigate ejector geometry, sizing, fluid dynamic behavior, thermodynamic performance, and binary fluid performance without the need to physically fabricate trial ejectors, use actual fluids, or construct operating test systems (cost & time saving measures).
3. The design and fabrication of a gas/gas test apparatus to test the performance of various ejector geometries, jet nozzle designs, and gas-phase fluid pairs (such as Argon with Nitrogen for example; also cost & time saving measures).
4. The development of analytical and empirical design strategies for ejector body, jet nozzle geometry, and sizing required to efficiently process a binary fluid pair consisting of two chemically distinct fluids.
5. Research, analytical exams, numeric simulations (CFD), and empirical testing to identify and validate what material properties impact the performance of binary fluid pairs. This goal involved the development of proprietary algorithms used to search and assay fluids in the NIST database. These critical fluid material properties were found to be relative molecular mass, ratio of specific heats (i.e. the adiabatic index), ratio of phase change

enthalpy and specific heat, and relative saturation pressure and temperature (relative meaning secondary versus primary fluid).

6. Establish the operating conditions necessary for a BFE space cooling demonstration system. This included temperature, pressure, mass flow rates, ejector behavior for varying cooling loads, system energy consumption limits, cooling capacity, and real world operational behavior.
7. Identification and sourcing of binary fluid candidates that meet the operational and environmental constraints imposed by a commercial 2 refrigeration ton demonstration system. In collaboration with DuPont, two such binary fluids were identified.
8. The design, fabrication, and testing of a Binary Fluid Ejector operation with a fully instrumented test system comprised of a boiler, evaporator, and a condenser suited for operating with the candidate binary fluid(s).
9. Empirical data collection, analysis, and performance evaluation of the ejector, binary fluid, and heat exchanger system in terms of energy consumption versus useful refrigeration produced (COP), and other critical ejector performance metrics such as entrainment ratio, compression ratio, ejector stability, binary fluid mixing behavior, and others.

c) Technology Description

The heart of the BFE concept can be encompassed by four primary questions posed at the beginning of the project.

1. Can the fluid material properties having the highest impact on BFE ejector and system performance be identified?
2. If such material properties exist, are fluids commercially available that have low environmental impact, that are nonflammable and nontoxic, and that have low enough cost for initial testing and evaluation? (Production cost in high quantities is a follow-on issue.)
3. Can an ejector be designed to effectively operate with, and efficiently process, two chemically distinct binary fluids?
4. Is the performance enhancement of binary fluid operation insignificant, or significant enough to support commercialization of BFE for any application (specifically for space cooling applications for this effort)?

An appreciation for these questions is essential to understanding the core technology concepts of BFE operation and performance.

Configured for refrigeration duty, i.e. space cooling, a BFE system is comprised of a forward Rankine thermal cycle, coupled to a reverse Rankine thermal cycle, by a gas phase ejector functioning as an expansion engine to compress the refrigerant gas.

The forward Rankine cycle operates similarly to an Organic Rankine Cycle (ORC) power generation system, where an organic fluid is boiled at moderately high temperature and pressure, and this high pressure gas drives a turbine or other type of expansion engine to produce useful work, such as driving a mechanical compressor for example. Such a system would include a boiler, a condenser (to condense the gas back into liquid phase and return it to the boiler), and an expansion engine or turbine driving some device to produce useful work, such as an electric generator or compressor in the case of an ORC refrigeration system. In the BFE case, the boiler and condenser are analogous, but the expansion engine is replaced by a supersonic jet nozzle within the ejector body. The high pressure gas issuing from the jet nozzle lowers the pressure in the ejector to less than the pressure in the evaporator, and it also supplies the energy for compressing the secondary gas refrigerant generated by the evaporator. The jet nozzle is the engine of the ejector compression process.

The reverse Rankine cycle is the same thermal process used for all refrigeration systems, including space cooling. It is comprised of an evaporator absorbing heat at low temperature (thus cooling warm air), a condenser that condenses the gas refrigerant back to liquid phase (which is returned to the evaporator through an expansion valve), and an electric motor driven mechanical compressor that compresses the refrigerant gas generated by the evaporator and delivers it to the condenser. In the BFE case, the evaporator and condenser are analogous, the electric motor is the jet nozzle, and the mechanical compressor is replaced by the ejector body. Low pressure refrigerant gas is drawn into the ejector body by the low pressure zone produced by the supersonic jet stream (from the nozzle), entrained or mixed with this fast moving stream of primary gas, whereupon its velocity is increased, and is then compressed through a process known as velocity stagnation, the physics of which are beyond the scope of this report.

The binary fluid ejector functions like an expansion engine (the supersonic jet nozzle), driving a mechanical compressor (the geometry of the ejector body). However, these two functions are accomplished fluidically, i.e. without any moving mechanical parts. Hence, a BFE space cooling system is comprised of a boiler, an evaporator, a fractionating condenser (because it also separates the two fluids), and a fluidic expansion engine and compressor, which is the jet nozzle and ejector body working together.

For a traditional ejector refrigeration system using a single fluid, water steam for example, the use of that single fluid represents a compromise between boiler/condenser energy efficiency, the forward Rankine loop (the drive cycle), versus evaporator/condenser energy efficiency, the reverse Ranking loop (the refrigeration cycle). This compromise in the two thermal cycles is present because a single fluid cannot be optimized for both drive <u>and</u> refrigeration duty. This so because the fluid material properties that produce high energy efficiency for the forward Rankine drive cycle, i.e. the boiler, expansion engine, and condenser, are different and opposed to the fluid material properties that produce high energy efficiency for the reverse Rankine refrigeration cycle, i.e. the evaporator, compressor, and condenser. Using a binary fluid, each individual component thereof optimized for these two requirements, drive cycle and refrigeration cycle, solves this dilemma. The Binary Fluid Ejector and its associated system represents an innovative solution to transforming medium and low grade thermal energy directly into useful work of refrigeration, and it does so with no moving mechanical parts for the engine/motor and compressor functions required to accomplish refrigeration using phase change fluids.

d) Scope of Work Overview

The scope of work required to accomplish the goals set forth in this project is quite diverse with respect to fields of science such as fluid mechanics, thermodynamics, and physics, multidisciplinary with respect to expertise in the science and engineering at hand, and extensive with respect to the number of tasks required for research, literature review, development of analytical and numeric simulation tools, prototype design and fabrication, test rig design and fabrication, data collection, analysis, and performance evaluation. As an overview, the following is provided.

Traditional Ejector Function
This work element involved understanding traditional ejector function and fluid dynamic behavior. This included fluid mechanics, thermal dynamics, supersonic shockwave behavior, jet stream primary core dynamics and function, fluid entrainment and mixing behavior, primary fluid expansion dynamics, secondary fluid acceleration and compression dynamics, jet nozzle geometry, sizing, and performance, ejector body geometry, sizing, and performance, as well as single fluid material properties and their impact on ejector operation and system performance.

Binary Fluid Material Properties
This work element was evolutionary in nature, and codependent with analytical, numerical, and empirical information that had to be discovered, developed, or otherwise collected and assessed. Tool building for this task was diverse and complicated, which required a combination of a high level perspective of the entire set of fluid mechanics, thermodynamics, and physics at play, with an intimate understanding of, and detailed expertise with, thermos-physical fluid properties, computational fluid dynamic modeling, refrigeration thermal cycles, and systems engineering. Mathematics and computer programing also played a significant role in this work element, for example the development of an algorithm and the expertise to use it, which was designed to search and assay thousands of binary fluid pair candidates.

Binary Fluid Ejector Design
When this project began, there existed no roadmap for the design, behavior, or performance of an ejector specifically designed to process two chemically distinct organic fluids. Although the basis of this work element started with existing ejector geometry, fluid behavior, fluid entrainment and compression governing equations, as well as some research literature that was instructive with respect to single fluid operation, fundamental questions had to be first envisioned, protocols and strategies developed to address these questions, and then the design and fabrication of prototype jet nozzles, ejector bodies, and test apparatus so performance data could be collected for validation of the expected results or behavior. This process was also evolutionary in nature, and codependent with data collection and analytical techniques developed from previous tasks.

Design, Fabrication, & Testing the Jet Nozzles, Ejector Bodies, Binary Fluids, & Test Rigs
These tasks were evenly distributed throughout the project term, and required the assistance of more than a hundred outside consultants, engineers and engineering firms, collaborative graduate students and professors, machine shops, drafting services, fluid material experts, 3D printing experts and contractors, sensor and control valve experts and suppliers, welders, electricians, and pipe fitters, accompanied by thousands of associated emails, phone calls, and meetings.

With the help of CCEMC funding, and patience, a great deal has been learned, and the beginning of an innovative refrigeration technology has been birthed, tested, and validated.

3. Outcomes and Learning

a) Literature review

The Binary Fluid Ejector (BFE), being developed by MRTS, is a thermally-driven fluidic compressor that replaces the electro-mechanical compressor in reverse-Rankine thermal cycles (refrigeration/heat pump cycles). These widely used thermal cycles account for billions of kWh of electric energy and produce hundreds of millions of metric tons of atmospheric carbon yearly in North America [6, 7]. The BFE is an advancement of the entrainment (jet) pump principle where a supersonic stream entrains and mixes with a subsonic fluid of different physical and thermodynamic properties. The BFE includes important innovations which increase its efficiency over prior art. Many researchers have shown the need to improve performance in order to make ejector-based cooling economically more attractive. From a survey of the literature (Eam's *et. al*. (1995, 2002), Chunnanond and Aphomratana (2004a, 2004b)) the performance of an ejector refrigeration system depends greatly on the ejector configuration. It is known that the entrainment ratio (ratio between the secondary and the primary fluid mass flow rates) is one of the major parameters that influence the coefficient of performance (C.O.P.) of ejector refrigeration systems (E-RS) (Buyadgie *et. al*. (2010), Chunnanond and Aphomratana (2004b)). Furthermore, the use of two chemically distinct fluids employed separately in the forward and reverse Rankine cycles of an ejector refrigeration system can improve the C.O.P. (Buyadgie *et. al.* (2010)) when the selected binary fluids are chosen with optimal thermo-physical properties.

The main objective of the present study is to conduct an experimental investigation in order to estimate the system performance of a binary fluid ejector cooling system using environmentally and human safe fluids that can be used in multiple real world systems. The comparison between the binary fluid and single fluid system performance is the first objective in order to prove the BFE concept. A comparison between the empirical results and CFD modelling for the ejector performance estimation is also an important part of this study. Indeed, the validation of the CFD model allows proper prediction of the system performance for different operating regimes which is of high interest for future investigations.

b) Technology development, System installation, experimental procedure

<u>Vessel Design</u>

The design processes were divided into several steps.

- The first step was to list the operating conditions for a wide range of different organic liquids (e.g. Pressure limits: 1.9 MPag for the boiler, 100 kPag for the evaporator and condenser).
- The second step was to calculate fluid volumes and power of the electrical heaters needed for the above regimes (e.g. the power of the heater for the evaporator: 24 kW).

- ➢ The third step was to estimate the fluid volumes required for the vessels (The volume of the fluid in the boiler for one-day experimental batch-run: 90 L

Taking into account all the above, it was decided to start with design of the evaporator vessel, as it requires more volume and power capacity. The first design for the vessel configuration was proposed by MRT staff scientists, while the final design was completed by Combustion Solutions Inc. (see Figure 1a and 1b).

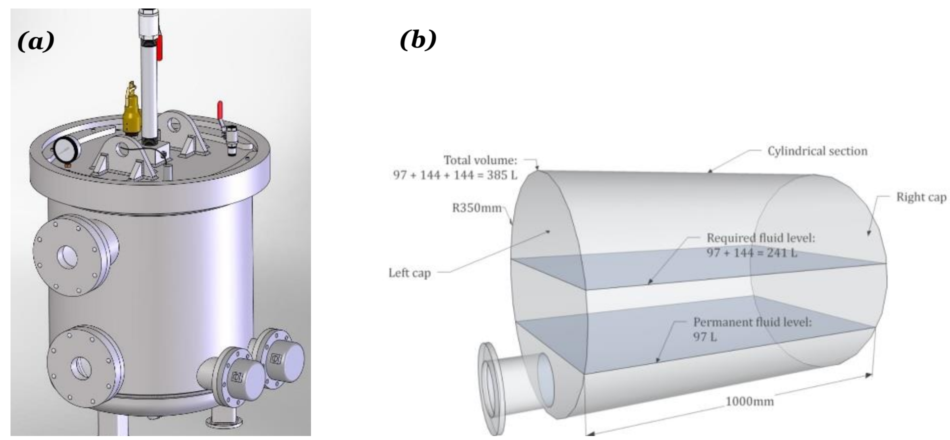


Figure 1. Vertical vs horizontal design of the pressure vessel

This vertical vessel design, 1(a), was not well suited for potentially expensive binary fluid:

- Two heaters were required
- The permanent "dead" fluid volume (the amount of fluid needed to cover the heat elements, that must be present at all times) was about 250 L
- Overall volume is about 900 L, which exceeded the specifications by more than 2 times

After careful review and discussion of the vertical vessel design, the MRTS group proposed an alternative evaporator design, which is schematically shown in Figure 1b. In contrast, this preliminary horizontal design had the following advantages:

- Single 24 kW heating element with the same watt density as the two 12 kW ones can be used
- The "dead" (permanent) fluid volume was reduced to about 100 L
- The total volume was reduced to about 400 L
- The position of the heating element facilitates liquid circulation during the boiling process

The evaporator and boiler vessels were constructed in identical fashion, which considerably reduced the associated manufacturing costs. The condenser vessel was designed in the same manner, and looks similar to the evaporator vessel. The main difference is that the material wall thickness is significantly less due to the lower temperature requirements in the condenser.

Ejector geometry

The most common geometry of a supersonic refrigerant ejector consists of a straight-sided convergent cone, a throat and a diffuser. The dimensions of different ejector parts are given in the Figure 3. This ejector geometry is based on that of Eams *et. al.*'s study (Eams *et. al.* (1995)). However, some differences exist between the geometries of that and the present study. For example, the curvature of the inlet of the mixing chamber is not given in Eams *et. al.*'s paper, hence a fifth order polynomial function is used in the present study. The empirical tests were conducted using a smaller ejector throat diameter (D) than that shown in figure 3 in order to scale down the BFE system. Additional CFD simulations were conducted for a larger diameter in order to improve the ejector performance for larger cooling capacity of the BFE system.

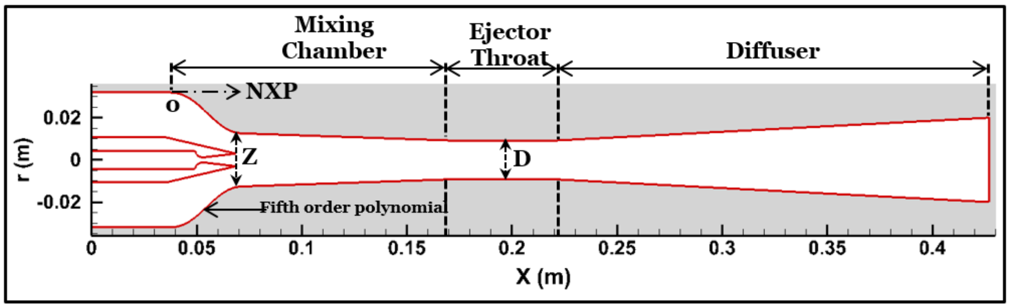


Figure 3. Schematic view and dimensions of the supersonic binary fluid ejector

The overall BFE test rig is shown in Figure 4. The system consists of the following main parts:

1. **Boiler (1.1 in figure 4)**
   1.1 Boiler vessel with ceramic band heater installed on the bottom outer side.
   1.2 Boiler piping, including control valve, superheater, pressure transducers, temperature sensors and mass flow meter (1.2 and 1.3, respectively)
2. **Evaporator (2.1 in figure 4)**
   2.1 Evaporator vessel with ceramic band heater installed on the bottom outer side.
   2.2 Evaporator piping, including control valve, superheater, pressure transducers, temperature sensors and mass flow meter (2.2 and 2.3, respectively).
3. **Condenser (3.1, 3.2 and 3.3 in figure 4)**
   3.1 Condenser vessel with spray nozzle (3.1)
   3.2 Catchment tank with ceramic band heater installed on the bottom outer side (3.2). Recirculating cooling system, including recirculating pump, heat exchanger, control valves, pressure transducers, temperature sensors and flowmeters (3.3).
4. **Ejector (4.1, 4.2 and 4.3 in figure 4**); Ejector assembly detailed view is presented in Figure 5.
   4.1 Ejector body: assembly of mixing chamber, throat and diffuser (2, 3 and 4 in figure 5).
   4.2 Ejector front end with nozzle traverse mechanism (1 in figure 5).
   4.3 Ejector back end with calming chamber buffer (5 in figure 5).
5. **Vacuum pump (5 in figure 4)**
   The vacuum pump is used to evacuate all incondensable gases (air) from the system before running binary fluid experiments.

LabVIEW system control:

LabVIEW main control panel was designed as a flow diagram showing schematically all system components, controls and sensors in real time. The control panel has a safety alarm system which automatically checks "system health" by monitoring many critical parameters pre-defined for specific operating regime (such as maximum boiler pressure, temperature, etc.). This safety subsystem shows alarms to operators (accompanied with alarm sound) and shut downs system components in case of reaching critical levels.

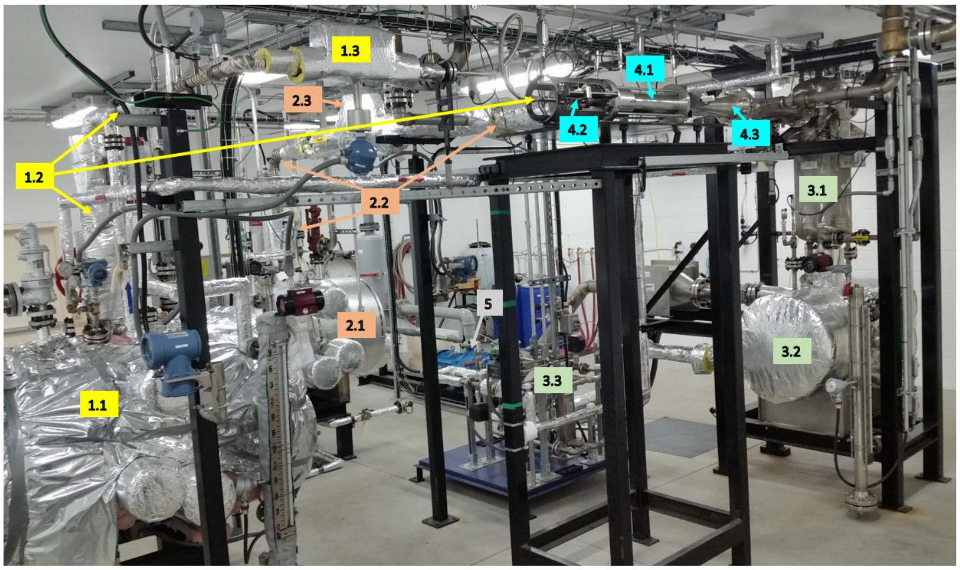


Figure 4. Overall BFE test rig view

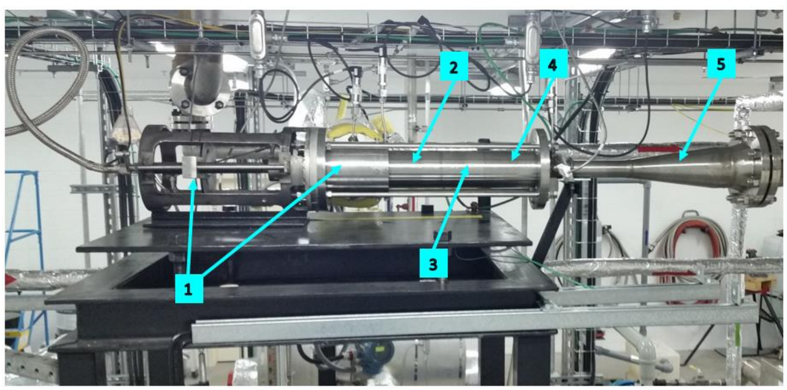


Figure 5. Picture of the ejector body including the front and the back ends

c) Modelling details

Computational Fluid Dynamics (CFD) model

A grid resolution study was performed to determine the optimum number of cells for grid independent results of the CFD modelling. Grid refinement was performed in regions of high pressure/velocity gradients and predicted locations of shock structures. The optimum number of grid cells was found between 260,000 and 340,000 for the different CFD cases. The time averaged Navier-Stokes equations for variable density flows (Favre averaged) were used. The temperature field was calculated by solving the energy equation, and the predicted pressure, density and temperature are related through the ideal gas law. For the binary fluids modelling, the properties of the primary and secondary fluids were provided by DuPont and used to solve the species transport equation. The commercial CFD package ANSYS FLUENT 15 was used to implicitly solve the governing equations. The SST *k*-omega turbulence model is used; this model was developed by Menter (1992) to capitalize on advantages of the *k*-omega model close to the wall and the *k*-epsilon ($k - \varepsilon$) turbulence model away from the wall. The simulations were deemed to be converged when the residual for each governing equation reduced to a value less than 10^{-6}.

Binary fluid pair assay and ranking

Selecting binary fluids with optimal material properties is critical to improving the performance of the BFE GSHP system. The fluid selection process aims to find fluids that will yield a low compression ratio for a given primary saturation pressure (P1 inside the boiler), as this will increase system efficiency. An iterative search of binary fluids was performed with two databases (NIST and YAWS handbook), containing a total number of pure components higher than 30,000 fluids. Several fluid pairs favorable to higher ejector C.O.P. were selected for different operating temperatures of the GSHP cooling system using the following formula for refrigeration cycle C.O.P.:

$$COP = \omega \frac{Hv_{Evap} + \overline{Cp_1}(T_{Cond} - T_{Evap})}{Hv_{Boil} + \overline{Cp_2}(T_{Boil} - T_{Cond})} = \omega\, f_h$$

Where Hv_{Evap} and Hv_{Boil} are the enthalpy of vaporization at the evaporator (secondary fluid) and the boiler (primary fluid) temperature, respectively; $\overline{Cp_1}$ and $\overline{Cp2}$ are the mean liquid phase specific heat capacity of the primary fluid (between boiler and condenser) and the secondary fluid (between evaporator and condenser); T_{Boil}, T_{Evap} and T_{Cond} are respectively the saturated temperatures in the boiler, evaporator and condenser and ω is the mass entrainment ratio. The parameter f_h is introduced to represent the term:

$$\frac{Hv_{Evap} + \overline{Cp_1}(T_{Cond} - T_{Evap})}{Hv_{Boil} + \overline{Cp_2}(T_{Boil} - T_{Cond})}$$

Despite the favorable thermophysical properties of some binary fluid candidates in the NIST database, the final fluid pair chosen to be tested in our lab was donated by our industrial partner 'DuPont'. The main reason is the safe aspect and the low environmental impact of this fluid pair as compared to those selected from the 2 fluid databases previously discussed. In fact, the Vertrel Sinera – Vertrel XF combination presents non flammability and low toxicity. They can thus be used for residential and commercial applications. It should be also mentioned that the T_{cond} is replaced by the temperature of the condensed primary fluid recirculating from the condenser to the boiler. In the case of Sinera, this temperature is around 70C which is favorable to a higher COP as will be shown in this document.

d) **Results of experiments, model simulations and analysis of results**

Binary fluid experiments and thermal C.O.P. predictions

The two operating regimes studied in this paragraph were chosen in order to cover a wide range of operating regimes for the heat pump cooling application. The temperature gradients (between evaporator and condenser) range from 9.5 to around 19C and the corresponding compression ratios from 1.07 to 1.50, respectively. Once the CFD prediction of the ejector performance is validated for different flow dynamics inside the ejector, additional real world operating conditions can be investigated using the CFD model.

Table 1. Selected operating regimes of the BFE cooling system

	Q_{m1}	Q_{m2}	P1	P2	P3	T1	T2	T3	CR	ER	fh	C.O.P.
	g/s	g/s	kPs-abs	kPa-abs	kPa-abs	C	C	C				
Empirical results	7.16	5.74	376.47	17.98	27.00	168.32	14.20	33.00	1.50	0.80	0.75	0.60
	4.70	8.35	248.50	35.58	37.92	172.92	27.58	37.01	1.07	1.78	0.75	1.34
CFD prediction	7.10	5.97	376.50	17.98	27.00	159.00	14.10	33.00	1.50	0.84	0.75	0.63
	4.72	8.84	248.50	35.58	37.92	172.90	27.60	37.00	1.07	1.87	0.75	1.40

Note:

- P1, P2 & P3 are respectively the saturation vapor pressure of the primary fluid (boiler), the secondary fluid (evaporator) and the fluid mixture (condenser).
- T1, T2 and T3 are respectively the saturated temperatures in the boiler, evaporator and condenser.
- Q_{m1} and Q_{m2} are the primary and secondary mass flow rates, respectively.
- CR and ER are the compression ratio (P3/P2) and the entrainment ratio (Q_{m2}/Q_{m1}), respectively.

Figures 6 and 7 show the presence of a recirculation region inside the ejector mixing chamber. For both cases, the recirculation region begins at about 10.5 cm downstream from the mixing chamber inlet, where the boundary layer separates. The recirculation region extend further downstream for the higher compression ratio despite the higher flow momentum of the supersonic jet core. It should be stressed that the lower compression ratio (CR = 1.07) results in a better energy exchange between the primary and the secondary flows and a smaller flow blockage (smaller recirculation region) inside the mixing chamber. Therefore, a greater entrainment ratio and ejector performance are observed for the lower compression ratio.

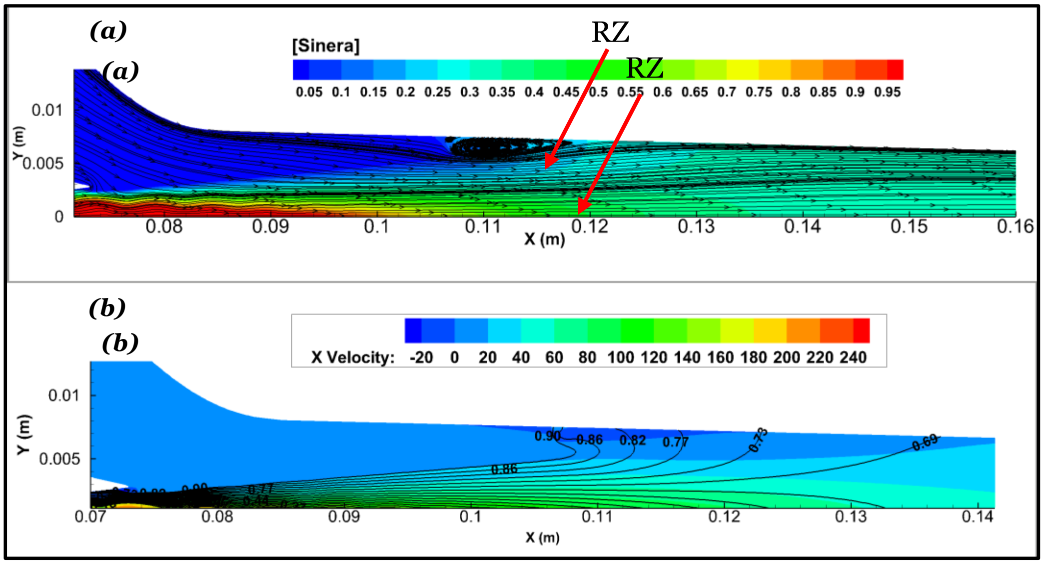
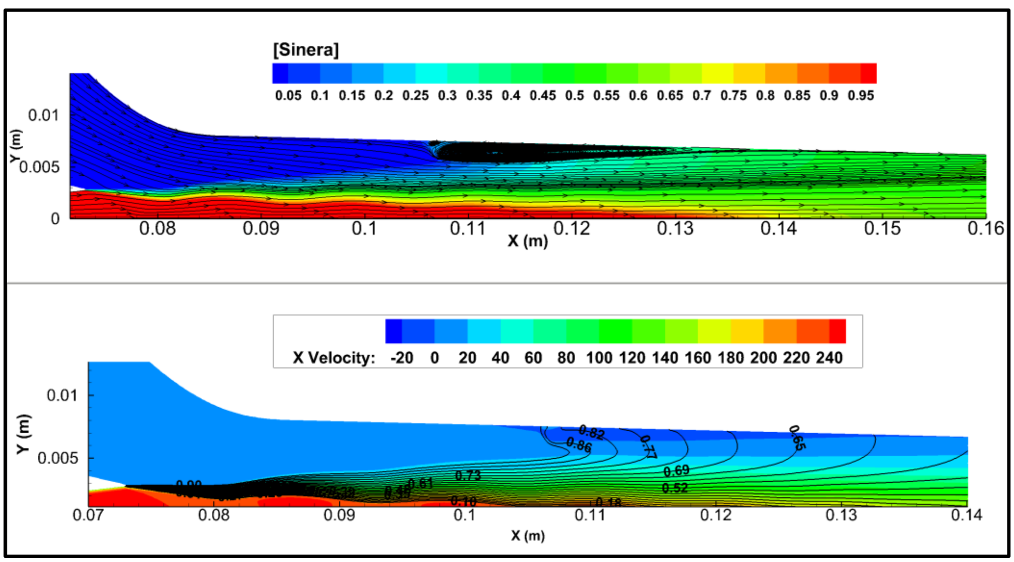


Figure 6. Flow dynamics inside the ejector for CR = 1.07 and P1 = 248.5kPa
(a) concentration of the primary fluid and streamlines; (b) stream-wise velocity and iso-lines of the primary fluid distribution

Figure 7. Flow dynamics inside the ejector for CR = 1.51 and P1 = 376.5kPa
(a) & (b) as per figure 6



The distribution of the static pressure for CR = 1.07 (figure 8a) shows an attenuation of the shock waves at around X = 0.10 m. At this location, a sharp increase in the static pressure is observed on the ejector wall. The pressure rise is related to the velocity drop in the flow recirculation region. A flow acceleration then occurs and results in a wall static pressure undershoot at the inlet of the diffuser (around X = 0.22 m). For the higher compression ratio (figure 8b) the attenuation of the shock waves occurs further downstream and the static pressure along the ejector wall does not show an undershoot mechanism. This would be explained by a better transition from the supersonic to the subsonic flow for the lower compression ratio.

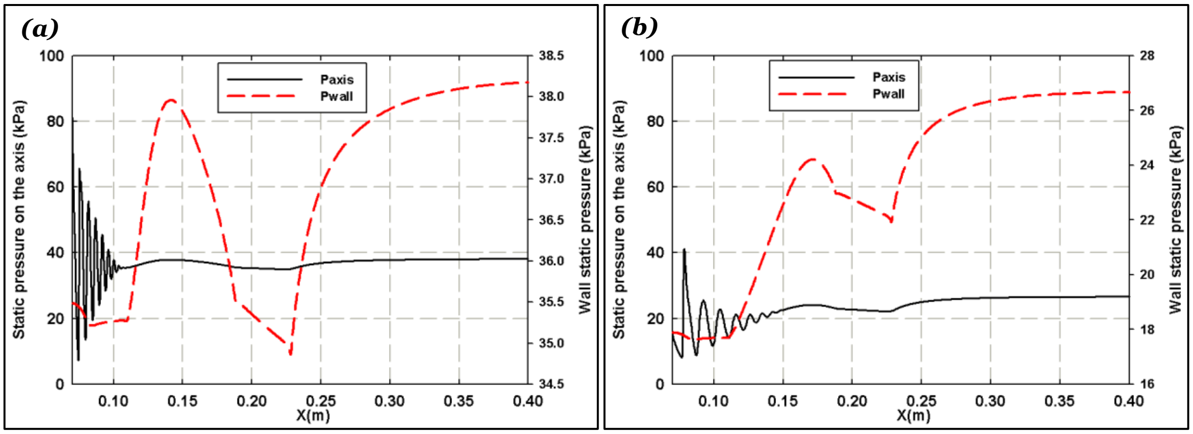


Figure 8. Static pressure distribution along the ejector axis and the ejector wall (a) CR = 1.07 (b) CR = 1.5

The influence of the primary pressure on the ejector performance is further investigated for the compression ratio CR = 1.2. The operating conditions of two CFD cases are shown in table 2. It is shown that the increase of the primary pressure for the same compression ratio resulted in more than a 100% increase in the ejector performance. Since the primary pressure of 254.4kPa doesn't provide sufficient momentum to increase the boundary layer resistance to the adverse pressure gradient, P1 was increased to 340 kPa. Such an increase in pressure amplitude leads to a better suction of the secondary fluid and in a quasi-optimal expansion of the supersonic jet inside the mixing chamber. The resulting entrainment ratio is significantly higher and the ejector performance is increased by around 96%.

Table 2. Influence of the primary pressure on the BFE system performance

Fluids	MM	T1	T2	T3	P1	P2	P3	CR	fh	Q_{m1}	Q_{m2}	ER	COP
	g/mol	C	C	C	kPa	kPa	kPa			g/s	g/s		
Sinera	362.09	143.7	20.17	32.10	254.4	28.35	32.85	1.2	0.89	4.80	3.82	0.80	0.71
XF	252.00												
Sinera	362.09	155.5	20.17	32.10	340	28.35	32.85	1.2	0.82	6.40	10.9	1.70	1.39
XF	252.00												

C.O.P. predictions of single fluid ejector cooling system

The thermal COP predictions of a single fluid ejector-based cooling system are presented in table 3 using either Vertrel XF or Water as working fluid (primary and secondary fluids). It is clearly shown that the use of a single fluid in the ejector refrigeration system leads to very low system performance when compared to a binary fluid combination. In fact, the high compression ratio (CR = 3.1) results in a flow separation and that extends along the whole mixing chamber and upstream towards the ejector secondary inlet. On the other hand, the best single fluid system performance is obtained for water-water when used at a boiler temperature of 180C. The resulting COP is equal to 0.37 which is much lower than that obtained with the binary fluid combination (Vertrel Sinera and Vertrel XF). It will be shown in next section that the COP increase by around than 300% for binary fluid system as compared to a single fluid system when the proper fluid combination and ejector geometry are being used.

Table 3. Operating regimes and system performance of a single fluid ejector

Fluids	MM	T1	T2	T3	P1	P2	P3	CR	fh	Q_{m1}	Q_{m2}	ER	COP
	g/mol	C	C	C	kPa	kPa	kPa			g/s	g/s		
XF	252.00	120.00	12.00	35.00	659	16.6	51.1	3.1	**0.82**	11.02	-10.6	-0.96	**-0.79**
XF	252.00												
water	18.00	145.50	14.00	33.00	420	1.59	5	3.1	**0.97**	1.99	0.2	0.10	**0.10**
water	18.00												
water	18.00	136.00	18.00	36.40	321	3.75	6.1	1.6	**0.99**	1.54	0.58	0.38	**0.37**
water	18.00												

1 C.O.P. predictions of BFE cooling system

As previously mentioned, the empirical tests were performed at a smaller scale because of the system limitation and the high fluid cost. The effect of the ejector scale on both the entrainment ratio and the COP is discussed in this section. The two cases presented in table 4 correspond to the geometry 1 (discussed in the other section; noted G1) and the geometry 2 (noted G2) which represents a cooling capacity more than 2.5 times larger than with the geometry 1. The main differences between G1 and G2 are the primary nozzle diameter which is 2 mm for G1 and 3.4 mm for G2 and the diameter of the ejector throat which is 11 mm for G1 and 18 mm for G2. Other internal dimensions of the ejector are also affected by the scaling-up of the BFE system. It is interesting to note that the scaling-up of the ejector not only affects the cooling capacity of the refrigeration system but also the ejector performance, and thus the system efficiency. A stronger interaction between the shock waves and the boundary layer flow for the smaller ejector could explain such difference. In addition, the smaller ejector would result in a narrower exchange surface between the two streams for the same jet expansion.

Table 4 also shows that a COP of 1.00 is achieved when the proper ejector geometry and operating conditions are being used. This is around 300% improvement in the thermal efficiency of the BFE refrigeration system as compared to single fluid system using water as working fluid.

Table 4. Operating regimes and system performance of a binary fluid scaled-up

Fluids	MM	T1	T2	T3	P1	P2	P3	CR	fh	Q_{m1}	Q_{m2}	ER	COP
	g/mol	C	C	C	kPa	kPa	kPa			g/s	g/s		
Sinera	362.09	170.00	12.00	35.00	469.5	16.6	28	1.69	0.78	8.88	8.26	0.93	**0.72**
XF	252.00												
Sinera	362.09	163.00	12.00	35.00	402	16.6	28	1.69	0.78	17.20	22.17	1.29	**1.00**
XF	252.00												

e) Project outcomes

The main findings of the present study can be summarized as follows:

1. The BFE concept was empirically demonstrated for real-world space cooling operating regimes. The experimental results shows that a thermal C.O.P. between 0.60 and 1.34 is achieved based on the fluid properties and ejector performance. Future work, including optimization of the ejector geometry could increase the ejector performance even further.
2. The primary and secondary fluids were selected based on their favorable thermo-physical properties for the BFE space cooling application. An environmentally friendly and safe fluid pair with non-flammability and low toxicity were selected because of their potential to be used for both residential and commercial applications.
3. The choice of the ejector geometry is based on a literature review and a comprehensive CFD study conducted at MRTS to understand the influence of different parameters on the ejector performance. Therefore, ejector geometry improvement were possible in order to achieve a high system performance. It should be however noted that no geometry optimization was yet performed and this can further improve the BFE system performance by more than 10%.
4. The CFD model, used for the flow dynamics and ejector performance predictions, was validated for different operating regimes. Therefore, additional operating regimes were studied using the CFD model and the flow dynamics inside the ejector was investigated and discussed using the validated CFD model.
5. Single fluid ejector simulations (using Vertrel XF or water as working fluids) were conducted and compared to the Binary Fluid performance. It was found that for the same operating temperatures, the higher compression ratio when a single fluid is used results in a dramatic decrease in the ejector performance. For example, the use of the Sinera-XF combination results in 300% thermal COP increase as compared to a water-water system.

f) Discussion

The present BFE empirical study is an important step in realizing the commercial BFE cooling system. In addition to proving the BFE concept, the CFD model was validated and the system performance are promising for further development of a commercial BFE prototype. For example, a detailed description of the flow dynamics, for various operating conditions, obtained from the validated CFD model can be used for a good understanding of the mixing mechanism, and thus the entrainment, which is of high interest for the proper choice of ejector geometry according to the fluids properties and the system operating conditions. In addition, further improvement of the system efficiency and ejector geometry optimization can be achieved using CFD modelling.

It is known that the thermal C.O.P. is very sensitive to the compression ratio, which is the ratio between the equilibrium saturation pressure of the fluids mixture in the condenser (back pressure), and the saturation pressure in the evaporator (secondary pressure). Therefore, the BFE cooling system performance was considered in the present study for a wide range of compression ratios in order to simulate the effect of the operating condition variations on the system performance. It was demonstrated that the proper choice of the ejector geometry leads to its operation at high compression ratios. The primary saturation pressure and the primary nozzle throat diameter strongly affect the momentum of the supersonic jet, the expansion of the jet and the strength of the shock waves inside the ejector. Therefore, these parameters need to be properly chosen for a given compression ratio and fluid candidates to ensure better entrainment of the secondary fluid and sufficient mixing between the primary and the secondary fluids.

It should be noted that the condensation and fluid separation energy should be considered in future work in order to be considered in the system C.O.P. calculation. Further ejector geometry optimization is in progress in order to further improve the BFE performance. Furthermore, passive and/or active flow control strategies are being developed to remove regions of flow separation and improve the mixing between the primary and secondary fluids, in order to further enhance the BFE cooling system performance.

g) Important lessons learned

The present project was a great opportunity for the development of a multi-disciplinary knowledge using numerical and empirical methods in order to design and build a thermally driven heat pump that would present a wide range of applications. The main lessons learned are of high importance for the success of this project. They can be summarized as follows:

1. The most important lesson was that the use of a binary versus a single fluid for ejector refrigeration can offer a significant improvement in performance.

2. Since the system design is very sensitive to the operating regimes, a detailed literature review regarding these operating conditions based on real world application should be the starting point for such project.

3. Under certain operating conditions (e.g. high temperature gradient between the evaporator and the condenser) the ejector performance can be strongly affected. Therefore, the proper choice of the ejector geometry is critical in order to enhance the mixing inside the ejector and improve the overall efficiency of the BFE system.

4. The binary fluid selection should account for the temperature lift between the evaporator and the condenser since the ejector performance is very sensitive to the compression ratio across the ejector. Proper binary fluid selection should consider:
   - The choice of favorable thermos-physical properties of the selected fluids for both the Rankine and reverse Rankine cycle of the BFE refrigeration system.
   - The interaction between the two working fluids because of its impact on the compression ratio and the selection of the separation method.

5. The CFD model should be validated using experimental results. Particular attention should be given to the choice of the CFD model because of the complex flow dynamics inside the ejector. Once validated, the CFD model can be used for ejector geometry optimization purpose. In addition, deeper understanding of the flow dynamics inside the ejector can be obtained using CFD modeling. Therefore, flow control methods can be proposed in order to improve the mixing process and to reduce the flow blockage for a better ejector performance.

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4. Greenhouse Gas and Non-GHG Impacts

a) Greenhouse Gas Benefits

The Binary Fluid Ejector (BFE), being developed by MRTS, is a thermally-driven fluidic compressor that replaces the electro-mechanical compressor in reverse-Rankine thermal cycles (refrigeration/heat pump cycles). These widely used thermal cycles account for billions of kWh of electric energy and produce hundreds of millions of metric tons of atmospheric carbon yearly in North America [6, 7]. BFE technology can reduce GHG emissions (and other air pollutants associated with power plants) through:

1. Increased use of renewable energy

   The initial market launch for BFE will be as the cooling component for a BFE CCHP device. As such it will provide space cooling using waste heat, a renewable energy, as its drive energy versus the electrical energy used to drive conventional space cooling devices. BFE can also be driven by solar thermal energy, geothermal, biogas or any other thermal renewable energy.
2. Use of more environmentally friendly refrigerants.

   BFE technology will use working fluids with lower GWP than current main-stream refrigerants for electrical heat pumps and air conditioners, reducing emissions associated with manufacturing of products and system leaks.

b) Quantification of Environmental Benefits

It is believed that the BFE cooling component is an enabling technology that will help expand the deployment of CHP systems which, in turn, will cause carbon and emissions reductions due to the waste heat being used for heating rather than additional consumption of primary fuel for heating. Each EnerG 385 CHP device will, over its 15 year life, result in the savings of approximately 18,000 tonnes of GHG. If, as stated in the DOE study referred to above, that "*Sensitivity analysis indicates that improvement in the installed cost and efficiency* [of CCHP systems] *increases the market size dramatically"*, then BFE could have a significant indirect impact on emissions management by increasing CHP deployment.

In terms of direct impact, a BFE device driven by waste heat, will produce GHG savings equal to the offset of the electricity production required to achieve the same cooling capacity with an electromechanical system.

The average Canadian figures for power production have been used to calculate benefits from BFE introduction. This includes the following figures as per the SDTC Emissions Factors Database:

- Canadian national average electric generation: **200 gCO2e/Kwh**
- Rest of World electric generation: **502 gCO2e/Kwh**

BFE CCHP unit savings

Per units savings for BFE CCHP are illustrated in the table below. For this table, only savings that result from the cooling portion of the CCHP system, i.e. directly from the BFE component, are considered. For each installation the BFE system component will deliver the 20 RT of cooling, or 70 kW output. A typical electrical AC system of the same output would require 23.33 kW of grid power input drive energy. The amount of emissions savings per year is a function of utilization. A utilization factor of 25% is assumed for commercial buildings in Canada, 50% for commercial buildings in the U.S. and the rest of the world.

Table 5: Per Unit Savings for a BFE CCHP

Annual Grid Power Avoided per BFE Unit	Canada	United States
BFE Cooling Capacity (RT)	20	20
BFE Cooling Capacity (kW)	70	70
Rqd Grid Power for Electric AC with COP of 3.0	23.33	23.33
Cooling Unit Utilization Factor	25%	50%
Cooling Hrs/year	2,190	4,380
Avoided Grid Power / BFE Unit / year (kWhrs)	51,093	102,185
Annual GHG Reduction / BFE Unit		
Reduction Factor (gms CO2e/kWh)	200	502
Annual Reduction (gms)	1.02E+07	5.13E+07
Annual Reduction / BFE Unit (tonnes)	10.22	51.30

Potential Reduction in North American GHG Emissions

Table 6 on the right shows the number of buildings that fit within the prime target categories for installation of a CCHP system. This list does not include shopping centers, municipal buildings, warehouses or industrial applications. Assuming that, at market maturity, BFE equipped CCHP systems are installed in 1% of these target buildings, then the total installation would be 45,000 buildings. However, the average installation would use two 20 RT units. This would mean a total of 90,000 BFE units in place.

	Total Number Target Buildings
US and Canada	
Education	124,623
Nursing Homes	22,562
Lodging	58,562
Gymns/Health Clubs	33,500
Offices	858,400
Multi Family (Condo)	3,420,000
	4,517,647

Table 6: Target Building Types

Under such an assumption, the total annual reduction in GHG emissions for North America would be 4.3 million tonnes as shown in Table 7. The world market for AC is approximately three times as large as that of North America. Hopefully BFE would also play a major role through deployment in countries from the Middle East through South East Asia which have hot climates and greater need of self-generation due to problems with central power grids.

Table 7: BFE Reduction of GHG

Annual Reduction in GHG Emissions Resulting from BFE Deployment.		
Annual GHG Reduction / BFE Unit		
Reduction Factor (gms CO2e/kWh)	200	502
Annual Reduction (gms)	1.02E+07	5.13E+07
Annual Reduction / BFE Unit (tonnes)	10.22	51.30
Annual GHG Reduction at BFE Market Maturity		
No. BFE Units Deployed at Maturity	9,000	81,000
Annual GHG Savings from BFE (tonnes/yr)	91,967	4,155,063
Total Annual GHG Reduction (tonnes)		**4,247,030**

c) Non GHG Impact

BFE can offer important environmental benefits other than reduction in GHG emissions. Some examples:

1) Conservation of Water for Cooling Towers

In EPRI's Summer 2007 Journal Article titled "Running Dry at the Power Plant", concern is expressed over the increasing competition for decreasing water supplies in the western U.S. The situation has only gotten worse in the last 8 years of extremely high average temperatures. Thermoelectric power plants extract as much water for their cooling towers as is extracted by agriculture. Though most of this is returned to aquafers or surface water, the input volume is still required and the hot water discharge from 'once through' cooling or the water loss from evaporative towers can have a significant environmental impact. Air cooled condensers for power plants require a great deal of surface area (capital cost) and in the high ambient temperature conditions that are often prevalent in areas of water shortage, they result in decreased power plant efficiency.

MRT has already studied a design for cooling the condenser of a building's primary AC system. The same principle can be employed to use the waste heat from the power plant to drive a BFE cooling system designed to give enough cooling to the inlet air temperature of the plant condensers to make air cooled towers more efficient.

2) Remediation of Process Affected Water

MRTS believes that distillation remains, from a technical perspective, the best application for an ejector based system. An obvious opportunity is desalination. Currently reverse osmosis membrane desalination produces relatively low cost water. However, approximately 20% of the desalination plants recently commissioned were thermal effect plants because they were located in regions with too high a salinity for RO membranes. These membranes also have difficulty treating tailings ponds. These tailings ponds have been difficult to remediate in a cost effective manner.

All of the technical solutions proposed to date seek to consolidate the tailings to the point that they can be dry stacked and stable enough to cover with a top burden through natural evaporative drying, centrifuging, chemical treatment, or a combination thereof. In none of these approaches is there any attempt to recover the value of clean water or any high end hydrocarbons contained within the tailings. Such recovery can be effected through the use of fractional distillation of the tailings, an approach which has been ignored to date because of the high energy cost associated with distilling such large volumes. However, distillation is economically feasible if a system can be employed that reuses the phase change enthalpy associated with distillation so as to dramatically reduce the input energy required, and, importantly, accepts that input energy in the form of direct thermal energy rather than high grade electrical energy. The reuse of phase change enthalpy is well established. Mechanical Vapour Compression systems are currently marketed which can reuse 95% of the energy required for evaporation. These mechanical compressors require high grade electrical energy. A BFE vapour compression system, driven by the waste heat from a power plant could provide a highly cost effective solution to remediating the tailings ponds while recovering valuable assets in the process – clean water and diluent.

5. Overall Conclusions

The following are the five primary conclusions from this research project

a) That there are 4 principle fluid properties that have a bearing on overall performance for a binary fluid and should be considered in any search for an ideal binary fluid. What is significant is the ratio, for each property, between the value of the primary fluid and the value of the secondary fluid. Two of these four properties had not been researched before. This conclusion was based on over a year of CFD simulations varying each of the conceivable fluid properties.

b) That a binary fluid ejector system is superior to a mono-fluid ejector system. The test with a DuPont fluid pair showed nearly a 300% improvement in COP for space cooling condition compared to an historical water/water steam jet ejector system.

c) That the COP potential for a BFE refrigeration system using fluids with ideal properties is extremely high. The primary energy COP for a space cooling system considers the ratio of useful heat moved to the primary thermal energy required to produce the electricity used by the compressor to move that heat. For an electromechanical AC system, the typical primary COP is .9 to 1.1. Based on CFD modeling, a BFE system, with an ideal fluid, would be two to three times as efficient. The impact for society could be profound if such fluids existed or could be created.

d) That to achieve the full potential of BFE, a binary fluid will have to be specifically engineered and manufactured. The current inventory of existing chemicals that could be searched (including 28,000 listed in the NIST database) yielded a disappointing low number of candidates, none of which had an excellent match to desired properties. Some fluids that would have been high performers were not commercially acceptable because they had a high global warming impact or were dangerous to use (toxic, flammable, explosive etc). Fluids that were safe to use, including the DuPont binary fluid, were well below potential in terms of performance.

e) That BFE should be a commercially viable product with a strong competitive advantage. Even with the safe, but low performing DuPont binary fluid, BFE still demonstrated a level of performance that would indicate an efficiency performance advantage and a projected capital cost advantage versus absorption chillers. Investing in a BFE device to use waste heat for space cooling should yield an attractive ROI.

6. SCIENTIFIC ACHIEVEMENTS

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7. Next Steps

a) Next Steps for BFE Technology Development

Through this CCEMC sponsored research project, MRTS was able to empirically demonstrate a Binary Fluid Ejector. Using the lower performing, but safe to handle (non-flammable, non-toxic) DuPont binary fluid pair, the test rig demonstrated an initial COP of .69 using a smaller, un-optimized ejector, in July, 2015.

The ejector used was designed for 2 RT operations, a capacity equivalent to a small residential central AC. This scaled down ejector suffers some an estimated 15% loss in efficiency compared to the planned commercial size because, with a smaller nozzle, the percentage of the fluid stream that is effected by drag from the sidewalls constitutes a higher percentage of the total stream than with the larger nozzles. It is anticipated that the same design in a larger commercial scale should have a COP of .75.

Such improvements in performance, together with the lower capital cost and greater reliability, should make ejector based refrigeration cycles highly advantageous over single effect absorption chillers. BFE has demonstrated the potential to be a viable commercial technology.

There is, of course, a great deal of further research and development required to make that transition from test rig to commercial product. The test run was performed on a batch basis without separation. This was a design requirement for the test rig because it had to be as flexible as possible to use different fluids in testing.

The design of an efficient fractionating condenser to separate the fluids is the next major objective. That design task is currently underway as a collaborative effort between Gas Technology Institute and MRTS. GTI will be manufacturing this fractionating condenser and shipping it to another collaborative partner, Ecologix Heating Technologies, Inc., an Ontario manufacturer of electric heat pumps and air handlers. Ecologix will build a 2 RT lab scale prototype system using the condenser from GTI, an ejector supplied by MRTS, and fluids supplied by DuPont (formerly DuPont), another collaborative partner.

Based on the results of the 2 RT Alpha prototype, work will begin on the construction of the 20 RT commercial prototype. A 2.5 year development and testing program has been laid out and submitted to SDTC for potential assistance in this effort.

As part of the commercial prototype project, there will be development work in a number of areas. The start-up and operating controls for the first prototype will be primarily manual. Ecologix has electrical and systems engineers on board that will be developing more sophisticated automation, strategies to respond to changing load conditions. The test rig in Calgary will be used for continuing evolution and testing of innovative ejector geometries with static and dynamic controls to improve ejector performance. It will also be used to test multiple ejector manifolds, with the capability of using different ejectors in response to different load conditions.

b) Long term plan for commercialization

The initial market introduction for BFE will be as an add-on component integrated into a co-generation system, often referred to as Combined Heat and Power (CHP) systems, to produce a tri-generation, or CCHP system, utilizing the waste heat from the generator component to drive the BFE device to produce space cooling.

In North America, buildings represent the largest percentage of primary energy end-use, greater than industrial use or transportation. The largest component of this building energy goes to heating and cooling requirements. Approximately 73% of residential energy is consumed in heating and cooling (including hot water). As the largest energy component in the largest energy consuming sector, buildings are an important focus of any effort to reduce energy consumption and GHG emissions.

The mix of cooling and heating loads will vary by climatic region, but most conventional HVAC systems in Canada generally deliver cooling through electrical air conditioning and heating through furnaces (natural gas or oil) or electric heaters.

One way to dramatically increase building energy efficiency is to combine distributed electric power generation with heating and cooling needs, in a CCHP system. Such systems reduce thermodynamic system losses encountered in main grid power plants, and extract greater efficiency from the fuel consumed (up to 85% for CHP and even greater potential for CCHP). Such a system would be configured so that a portion of the electrical needs of the building are provided by a natural gas burning power plant. This is typically a reciprocating engine but could be a micro-turbine, or fuel cell. Waste heat from this process would be used to reduce building heating needs in the winter, and, with BFE, to provide cooling needs in the summer.

BFE systems have significant advantage over absorptions chillers, not only in thermal performance, but also in their ability to scale down economically. The three major absorption chiller manufacturers in the U.S. do not offer any product smaller than 100 Refrigerator Tons (RT). According to a 2008 report from the DOE titled “A TAT [thermally activated technologies] Roadmap”, a 100RT AC unit is too large for 70% of all the commercial space in North America, and essentially all residential homes. There is currently no cost effective thermally driven heat pump available for residential or small/medium commercial buildings. As shown in the analysis below, due to the high capital cost relative to performance of an absorption chiller, adding such a chiller to a CHP system generally results in a reduced overall ROI and a longer payout than just installing the CHP system and using electric AC for space cooling.

A BFE equipped CCHP system targeted at 25,000 – 100,000 square ft. commercial space is believed to be the market segment with the greatest competitive advantage and the best "beach head" to introduce BFE technology. As shown in this cost/benefit analysis, BFE systems are anticipated to have a capital costs and an operational efficiency that will enhance the economics for CHP systems. Development of a BFE cooling component for commercial CCHP systems can be instrumental in increasing adoption of this environmentally beneficial solution to building energy needs.

c) Commercialization Related Actions

MRT has created a Calgary based subsidiary, Nexus Power Solutions, which began marketing CHP systems in June, 2015. The intent of beginning Nexus Power Solutions was not only to begin earning revenues but also, by marketing CHP systems, it is also pre-marketing BFE CCHP systems. Customers interested in purchasing a CHP system from Nexus, will have the added benefit of buying a platform which can be retrofitted with a BFE cooling component when it is commercially ready.

The president of Nexus Power Solutions, Dan Cloutier, was previously the president of Power Ecosystems, the CHP marketing company he founded in 2006. During his nine years there, Dan installed more CHP systems into commercial buildings than anyone else in Canada. His client base included many blue chip clients such as Oxford, Cadillac Fairview, Triovest, Atco, Melco, and others.

Steve Davies, president of Ecologix, has opened an Ontario office for Nexus Power Solutions and will use his engineering and sales channels to support the Nexus initiative.

Nexus Power Solutions has secured the rights to sell Ener.G CHP systems in Canada and the United States. Ener.G is a 30 year old UK company that makes an excellent product well suited to adaption with a BFE component.

The proposed business model is to bring Ener.G CHP systems into the Ecologix plant as a basic platform then convert them through the addition of a BFE cooling component and integrated electronic controls into an integrated CCHP device scaled for small to medium buildings. Ecologix has a 16,000 sq foot manufacturing facility.

These units will be marketed through Ecologix's dealers and distributors and directly by Nexus Power's marketing team and network channels.

d) Potential Partnerships under Development

One important opportunity is the ability to develop joint marketing arrangements with natural gas utility companies. They encourage the deployment of gas burning CHP systems and are particularly interested in seeing the development of more thermal refrigeration and cooling technologies.

Enbridge Distribution in Ontario believes that the upcoming cap and trade system that will be phased in to Ontario will require natural gas suppliers to develop more efficient utilization of natural gas. They see increased deployment of CHP as one of three key initiatives to meet their goals. Nexus has had initial meetings with Enbridge Distribution in Ontario and will be meeting again in December to introduce Steve Davies and the Ontario Nexus team. The goal is to work with Enbridge to promote CHP systems, and ultimately CCHP systems, to their customers.

Gas Technologies Institute has long been a supporter and collaborative partner in development of BFE technology. They have stated their willingness to introduce MRT to their gas utility members when it is commercially ready.

8. Communications Plan

MRT has not developed formal plans for communication to third parties. MRT has developed a descriptive power point presentation which was presented at the Banff Venture Forum and at the NREL Growth Forum (National Renewable Energy Lab) in Denver.

Presentations have also been made to the Canadian Gas Alliance, COSIA, various government agencies such as IRAP and SDTC, and to potential investors or joint venture partners, such as GE, DuPont, and 3M.