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INTEGRATION OF THE ACTIVE DESICCANT WHEEL IN CHP SYSTEM DESIGN

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ABSTRACT

A solid desiccant based ventilation system has been installed to provide ventilation, and cooling/heating as needed, to the Intelligent Workplace (IW) of Carnegie Mellon University, as part of the IW Energy Supply System (IWESS). Since its installation, extensive testing data have been collected and analyzed to characterize the operating performance and cost of each major component, namely the enthalpy recovery module, the active desiccant module, the heat pump module, and the overall system. It has been determined that the active desiccant wheel is expensive to operate due to the high price of natural gas in the current fuel market.

In order to improve the energy efficiency and reduce the operating cost of the overall system, it has been proposed to regenerate the active desiccant wheel using the rejected heat from a bio diesel engine generator. Given the temperature and quantity of the rejected heat available, performance maps that relate the supply air temperature and humidity with various system operating variables have been constructed for the proposed integrated system, based on the predictions from an equation-based performance model of the active desiccant wheel. Using the IWESS project as a specific example, a procedure has been outlined for developing operating strategies for the active desiccant wheel integrated Combined Heating and Power (CHP) system.

INTRODUCTION

A solid desiccant based ventilation system has been installed to provide ventilation, and cooling/heating as needed, to the Intelligent Workplace (IW) of Carnegie Mellon University, as part of the IW Energy Supply System (IWESS)[1]. As shown in Figure 1, the system integrates a 1.416 m^3/s (3000 cfm) circulation fan, a 50 kW air based heat pump for cooling/heating, and an active solid desiccant wheel, which can be used for air dehumidification in summer and air heating in winter. An enthalpy recovery module is included in this ventilation system to pre condition the ventilation air. This ventilation unit can be operated either as an air conditioning system, recirculating air from the building space and combining it with outside air for cooling/heating/ventilation in the space or as a Dedicated Outside Air System (DOAS), processing only the ventilation air[2,3,4,5]. For DOAS operation in summer, the outside air (OA) is drawn through the direct expansion (DX) cooling coil, where it is cooled and dehumidified. The air leaving the DX coil (LDX), is then split into two portions: one portion goes into the active desiccant wheel where it is further dehumidified (LDW); another portion bypasses around the wheel through a modulating damper. The warm dry air from the desiccant wheel is then mixed with the cold moist, probably saturated, air bypassing the wheel. The mixture is ducted into the IW. For a given application, the bypass damper is usually set at a certain position. The heat pump compressor and the desiccant regeneration air temperature are adjusted in order to obtain the operator specified supply air, SA, temperature and humidity under different outdoor conditions. This air handling process is represented in the psychrometric chart shown in Figure 2 for summer and winter design days in Pittsburgh.

Since its installation, extensive testing data have been collected using the instrumentation carefully placed at various locations in the machine. These data have been analyzed to characterize the operating performance and cost of each major component, namely the enthalpy recovery module, the active desiccant module, the heat pump module, and the overall system.

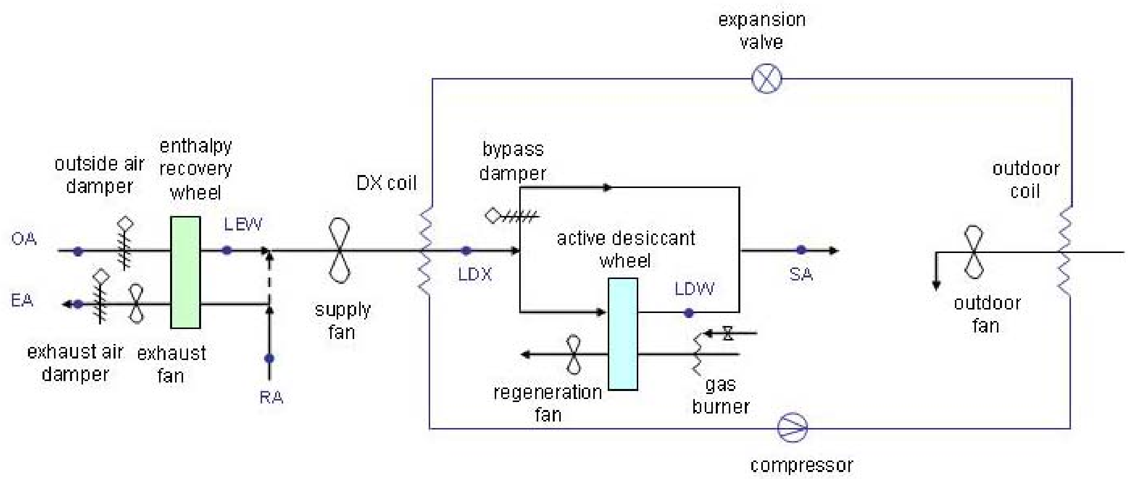

Figure 1. Flow Diagram of the Ventilation System Installed in the IW

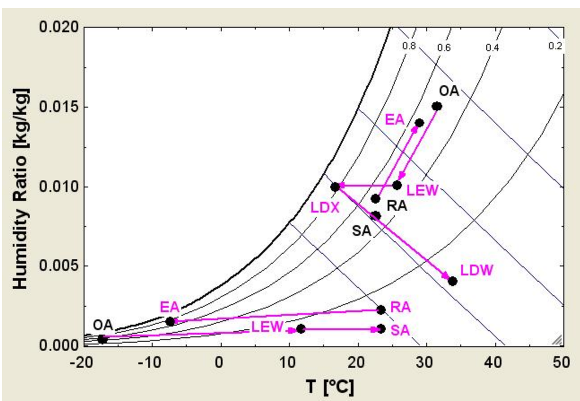

Figure 2. Psychrometric Chart Representation

This paper presents the operating performance and cost of the active desiccant module. Due to the high price of natural gas in the current fuel market, the cost of operating the active desiccant wheel is high, over 62% of the total operating cost of the system for typical summer conditions. In order to reduce the operating cost and improve the overall system energy efficiency, it has been proposed to regenerate the active desiccant wheel with the rejected heat from a bio diesel engine generator. With the aid of an equation-based performance model developed based on scientific and engineering principles, performance maps have been created for the proposed integrated system. These maps relate the supply air temperature and humidity to the various control variables in the system, including the regeneration air temperature, the regeneration air flowrate, the rotary speed of the active desiccant wheel, the bypass ratio around the active desiccant wheel and the leaving DX coil air conditions. Using the IWESS project as a specific example, a procedure has been outlined for developing operating strategies for the active desiccant wheel integrated Combined Heating and Power (CHP) system.

NOMENCLATURE

cfm	cubic foot per minute
CHP	Combined Heating and Power
DOAS	Dedicated Outside Air System
DX	Direct Expansion
EA	Exhaust Air from the Enthalpy Recovery Wheel
ESS	Energy Supply System
HVAC	Heating, Ventilating and Air Conditioning
IW	Intelligent Workplace
LDX	Leaving DX Coil
LDW	Leaving Active Desiccant Wheel
LEW	Leaving Enthalpy Recovery Wheel
OA	Outside Air
RA	Building Exhaust Air
RH	Relative Humidity
SA	Supply Air
VFD	Variable Frequency Drive

OPERATING PERFORMANCE AND COST OF THE ACTIVE DESICCANT WHEEL

For the system illustrated in Figure 1 and Figure 2, the required cooling and moisture removal are achieved by three components, namely the enthalpy recovery module, the heat pump unit, and the active desiccant module. The enthalpy removal, which includes both sensible and latent cooling accomplished by each of the three components at a typical summer operating condition, is plotted in Figure 3. The control settings corresponding to Figure 3 are

- OA condition: T = 28.9^{o}C, RH = 52.0%, w = 0.0139 kg/kg, v = 0.63 m^3/s
- RA condition: T = 23.9^{o}C, RH = 50.7%, w = 0.0090 kg/kg, v = 0.27 m^3/s
- SA condition: T = 19.1^{o}C, RH = 53.5%, w = 0.0073 kg/kg, v = 0.89 m^3/s

- Total heat removal: 22.0 kW
- Total moisture removal: 0.0048 kg/s

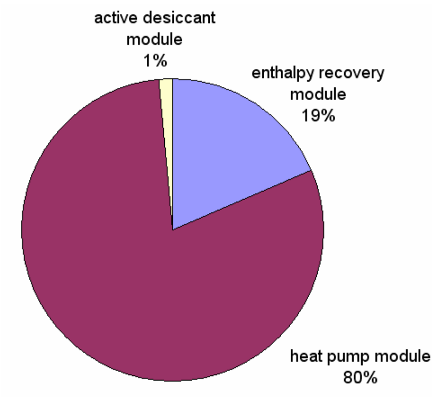

Figure 3. Enthalpy Removal Breakdown

It is seen that about one fifth of the enthalpy reduction is achieved by the enthalpy recovery module and the rest by the heat pump module. As expected, the active desiccant module made very limited contribution to enthalpy reduction, since the air temperature rises as its humidity is reduced. But enthalpy reduction is only part of the story in Heating, Ventilating and Air Conditioning (HVAC) operation; moisture removal has also to be considered since it affects occupants' thermal comfort and the operation of the sensible cooling devices such as radiant panels and fan coils. The moisture removal accomplished by each component is plotted in Figure 4. The active desiccant wheel provides more than half of the moisture removal; the rest is provided by the cooling coil and the enthalpy recovery module.

The operating cost of the system is shown in Figure 5. Among the three components in the system, the enthalpy recovery module has the lowest operating cost. The enthalpy recovery module only requires power input to operate the exhaust fan and to rotate the wheel, a very limited amount. The high price of natural gas in current fuel market is responsible for the high operating cost of the active desiccant wheel.

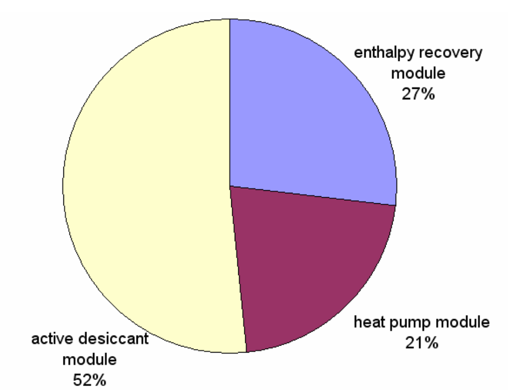

Figure 4. Moisture Removal Breakdown

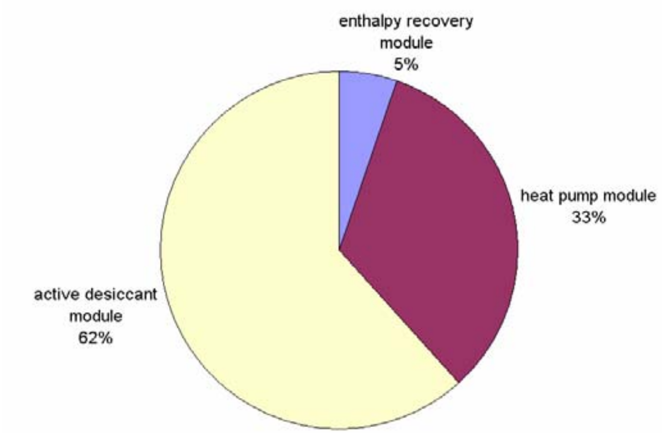

Figure 5. Operating Cost Breakdown

If the regeneration energy for the active desiccant wheel can be obtained for "free" or at significantly reduced cost from renewable energy sources or as the rejected heat from power generation systems, the overall operating cost of this ventilation system is expected to be reduced by approximately 60%. The efficiency of the overall integrated system is expected to be over 70%. The active desiccant wheel will become very attractive since relatively small amount of power is needed to run the regeneration fan and to rotate the wheel. This alternative is explored in this paper, using the IWESS as a specific example.

PERFORMANCE MODELING OF THE ACTIVE DESICCANT WHEEL

An equation-based model has been developed to predict the operating performance of the active desiccant wheels, based upon fundamental scientific and engineering principles. This model relates the active desiccant wheel's performance to its design parameters and operating conditions.

The design parameters include:

- the wheel dimension, such as the wheel depth, the wheel diameter and the split between adsorption and desorption sections;
- the channel dimension, such as the channel shape and size;
- the desiccant composite, such as the desiccant material properties and coating thickness, as well as the substrate properties and thickness.

The operating variables include:

- the rotary speed of the wheel;
- the inlet process air temperature, humidity and flowrate;
- the regeneration air temperature, humidity and flowrate.

The results from the model prediction are:

- the temperature and humidity of the process and regeneration air at any given time and location as well as the average values;

- the temperature and moisture loading of the desiccant composite at any given time and location as well as the average values.

This model has been validated using data collected from field experiments. Reasonable agreement between the experiments and the model predictions has been achieved. More information about the development and validation of this performance model can be found in [6,7].

DEVELOPMENT OF OPERATING STRATEGIES FOR THE ACTIVE DESICCANT WHEEL INTEGRATED CHP SYSTEM

The following questions need to be answered when integrating the active desiccant wheel in a CHP system:

- Are the desired supply air conditions achievable with the available regeneration air temperature and quantity?
- How should the variable control factors be adjusted in order to achieve the desired supply air conditions?

The following steps can be taken in developing operating strategies for the integrated system:

1. Determine the temperature and quantity of the rejected heat available from the upstream equipment.

For the IWESS project, a bio diesel engine generator has been installed as the prime mover. 20 kW thermal energy can be made available from the engine coolant, which is a mixture of glycol and water. It has been proposed to utilize this rejected heat from the generator to regenerate the active desiccant wheel in the cooling season. Due to spatial constraints, the engine generator is located in the basement of the building, six levels down from the ventilation system. It has been considered to make this rejected heat available to the ventilation system through two heat exchangers: a coolant-water heat exchanger located next to the engine generator and a water-air heat exchanger located inside the ventilation system. The heated water is used as the energy transfer medium, since it is more energy effective in transferring thermal energy from the basement to the ventilation system.

The quantity of the rejected heat from the engine coolant matches the regeneration energy requirement of the active desiccant wheel. According to the manufacture of the engine generator, the coolant temperature can go to 93^{o}C without affecting the engine performance. The approximation between the regeneration air temperature and the coolant temperature depends on the heat loss in the system and the design of the heat exchangers. With proper insulation on the piping and reasonable heat transfer areas in the heat exchangers, the regeneration air temperature can reach 70^{o}C. The measured regeneration temperature under natural gas operation is around 100^{o}C.

2. Determine the indoor, outdoor design conditions and the supply air requirements from the active desiccant wheel integrated HVAC system.

The ventilation system illustrated in Figure 1 and Figure 2 is assumed to operate as a DOAS that provides both the ventilation needs and the entire dehumidification requirements for a space, the IW in Pittsburgh, PA, with its maximum occupancy of 60 people. The DOAS supplies air at space neutral temperature and space cooling/heating is provided by hydronic, water-based, cooling/heating units.

The outdoor and indoor design conditions as well as the desired supply air conditions are as follows:

- Outdoor design condition: dry bulb temperature 29.2^{o}C, RH 63.3%, humidity ratio 0.0161 kg/kg;
- Indoor design condition: 23.3^{o}C, RH 50%, 0.00893 kg/kg;
- Desired supply air condition: 23.3^{o}C, RH 35%, 0.00622 kg/kg, flowrate 0.566 m^3/s

There are five variable control factors in this system: the regeneration air temperature, the regeneration air flowrate, the rotary speed of the active desiccant wheel, the bypass ratio around the active desiccant wheel and the leaving DX coil air conditions.

The regeneration air temperature and flowrate are obviously restricted by the upstream equipment, the engine generator. The maximum regeneration air temperature is limited by the coolant temperature. It is set at 70^{o}C in this example. The maximum regeneration air flowrate is limited by the amount of rejected heat available. It is determined to be 0.378 m^3/s.

3. Develop performance maps for the proposed integrated system.

In order to answer previous questions, performance maps that relate the supply air conditions and different settings of the variable control factors need to be developed. The supply air conditions are determined from the leaving DX coil air conditions, the leaving desiccant wheel air conditions and the bypass ratio based on the enthalpy and moisture balance of air mixing as seen from Figure 1. The validated performance model is used to predict the leaving desiccant wheel air conditions based on the leaving DX coil air conditions, the regeneration air conditions and the process air flowrate, which is a function of the bypass ratio.

Figure 6 through Figure 9 plot the predicted supply air conditions with relation to the wheel rotary speed and the bypass ratio around the active desiccant wheel, at various regeneration air flowrates. These plots assume a fixed leaving DX coil air condition: dry bulb temperature 12.4^{o}C and humidity ratio 0.00896 kg/kg, and a fixed regeneration air temperature 70^{o}C. The solid lines in these plots represent the supply air humidity and the dashed lines represent the supply air temperature. Different lines in the plots indicate different bypass ratio around the active desiccant wheel.

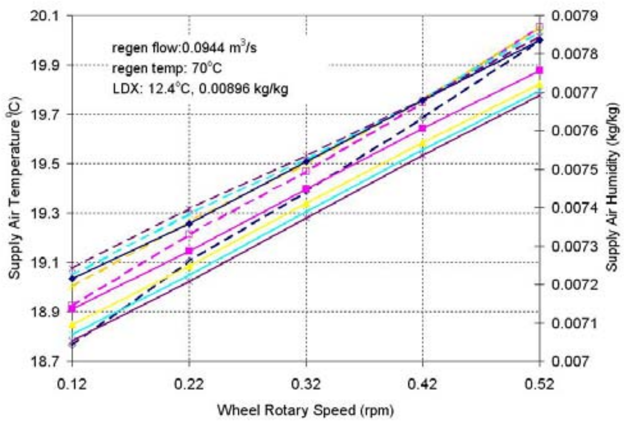

Figure 6. Predicted Supply Air Conditions with Relation to Wheel Rotary Speed and Bypass Ratio, Regeneration Flowrate 0.0944 m^3/s

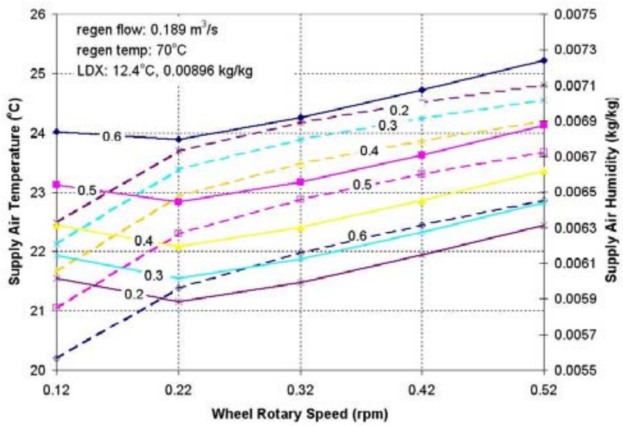

Figure 7. Predicted Supply Air Conditions with Relation to Wheel Rotary Speed and Bypass Ratio, Regeneration Flowrate 0.189 m^3/s

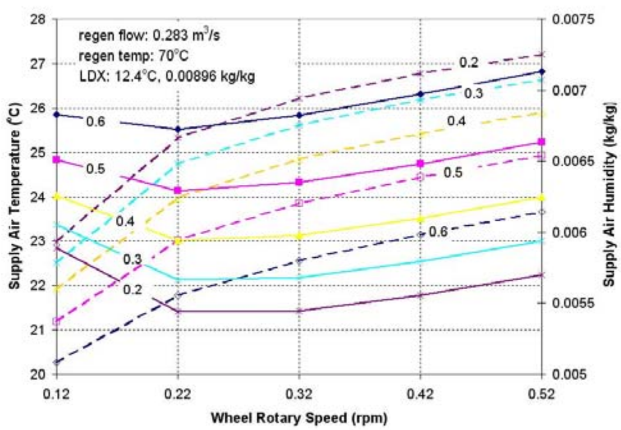

Figure 8. Predicted Supply Air Conditions with Relation to Wheel Rotary Speed and Bypass Ratio, Regeneration Flowrate 0.283 m^3/s

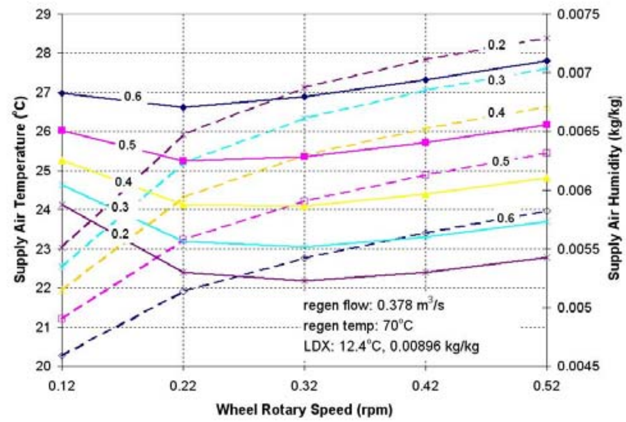

Figure 9. Predicted Supply Air Conditions with Relation to Wheel Rotary Speed and Bypass Ratio, Regeneration Flowrate 0.378 m^3/s

4. Determine whether the desired supply air conditions are achievable and how the various control factors should be adjusted.

As seen from Figure 6 through Figure 9, the supply air humidity decreases and the supply air temperature increases with decreasing bypass ratio. In addition, the supply air humidity decreases and the supply air temperature increases with increasing regeneration air flowrate. The desired supply air condition is not achievable with any bypass ratio when the regeneration flowrate is 0.0944 m^3/s. The desired supply air humidity is achievable with bypass ratio 0.2, 0.3 or 0.4, when the regeneration flowrate is 0.189 m^3/s. It is even obtainable with bypass ratio 0.5, when the regeneration flowrate is 0.283 or 0.378 m^3/s. The desired supply air humidity can not be achieved with any regeneration air flowrate when the bypass ratio is set at 0.6. For smaller bypass ratio and higher regeneration air flowrate, for example bypass ratio 0.3 and regeneration flow 0.378 m^3/s, the supply air temperature is lower than the desired value when the supply air humidity reaches the desired level. The lower supply air temperature means that the DOAS carries some space sensible load, which provides some freedom or safety factor in the overall system operation.

DISCUSSION

The previous performance maps are developed based on the selected leaving DX coil air condition and regeneration air temperature. The supply air conditions are solved as functions of the regeneration air flowrate, the wheel rotation speed and the bypass ratio. In a similar fashion, the supply air conditions can be solved as functions of the regeneration air temperature, the regeneration airflow and the leaving DX air condition, given a certain wheel rotation speed and bypass ratio.

Seen from the performance maps, the answer to the second question stated at the beginning of the previous section is not unique. The desired supply air condition can be obtained from different settings of the various control factors. A logical extension to the question would be: which settings will result in the lowest operating energy consumption or operating cost? It then becomes an optimization problem, with the operating energy consumption or cost as the objective function. This problem can be approached by defining the operating energy consumption or cost associated with the change of each operating variable and minimizing the objective function by varying the settings of the control variables.

Taking the ventilation system shown in Figure 1 and Figure 2 as a specific example, the optimization function can be described as:

Minimize (system operating energy consumption) = f(regeneration air flowrate, regeneration air temperature, leaving DX air condition, wheel rotation speed, bypass ratio)

The regeneration air flowrate is related to objective function through fan power required to push/draw the regeneration air through the active desiccant wheel. The regeneration air temperature is related to the objective function through the upstream equipment, the engine generator, and the loss when transferring the thermal energy from the engine generator to the ventilation system. In this system, the leaving DX air condition is controlled by adjusting the frequency of the compressor. Therefore the leaving DX air condition is related to the objective function through the energy use of the vapor compression system. The wheel rotation speed is controlled by adjusting the variable frequency drive (VFD) on the wheel motor. The wheel rotation speed is therefore related to the objective function through the power use of the wheel motor, which is limited. The bypass ratio is related to the objective function through the fan power required to push/draw the process air through the active desiccant wheel.

The sensitivity of the system operating energy consumption with regard to the different control variables can be obtained analytically or empirically from the system operation. The optimization can be then conducted based on the sensitivity study.

SUMMARY

In this paper, a procedure has been outlined for developing the operating strategies for the active desiccant wheel integrated CHP system. A validated performance model has been applied in predicting the supply air conditions from the integrated system under different settings of the control variables.

Performance maps that relate the supply air conditions and the different settings of the control variables have been constructed for the proposed system in the IWESS project. These performance maps show that the desired supply air condition can be achieved with certain settings of the control variables, namely the regeneration air temperature, the regeneration air flowrate, the leaving DX air condition, the wheel rotation speed, and the bypass ratio. The settings of the control variables to achieve the desired supply air condition are not unique. It is an optimization problem to determine the control settings to achieve the lowest system operating energy consumption or cost, in which the system operating energy consumption or cost is the objective function, and different control factors are the variables.

The proposed system configuration and operation presented in this paper is going to be installed and tested as part of the IWESS project. The test results will be compared with the predictions and reported.

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