A Tool to Assess Heating Efficiency of Direct-fired Heater with the Impact of Humidity Control

Wee Fong Lee and Peter P. Ling
Department of Food, Agricultural and Biological Engineering

Contact:
Wee Fong Lee lee.2010@osu.edu
Peter P. Ling ling.23@osu.edu

1. Abstract

Heating is one of the top two expenses of greenhouse operations in northern climates. Direct-fired heater (DFH) that has been promoted having high heating efficiency, 99.9%, compared to 80-94% of conventional indirect-fired heaters (IFH), could be an energy efficient choice. However, the high efficiency claim does not consider energy lost through air intake during combustion process. Fresh air intake is important for clean combustion and extra dehumidification for the water vapor generated from the combustion process to maintain a healthy environment for plant growth. The actual heating efficiency of a DFH is affected by amount of fresh air intake where higher air intake rate causes lower heating efficiency. A decision support tool (the tool, thereafter) was developed to determine the minimum air intake needs for the combustion and water removal, thus, the highest net heating efficiency of a DFH can achieve. In a case study, the tool predicted that a DFH had a net heating efficiency of 86%. The prediction was verified with field experiments to compare heating performance of the DFH to a popular IFH. The results showed varied DFH heating efficiency that was affected by the heater operation strategy to regulate fresh air intake rate. A higher heating efficiency was achieved with a fresh air intake rate determined by the tool. The DFH consumed 8.8% less fuel than that of the IFH. The field tested DFH heating efficiency was 87% which was in close agreement with the prediction of the tool.

2. Introduction

The proclaimed high heating efficiency and potential free CO_2 provider to the plants by DFH was an attractive rationale for greenhouse grower to invest in. However, growers who cared about their plants' health by looking into humidity control might lose their interest due to water vapor creation and DFH's actual heating efficiency reduction. Although DFH's efficiency was reduced, with proper air intake management, DFH's efficiency could be still feasible compared to conventional IFH. Therefore, this project aimed to develop a decision support tool to help growers to optimize their DFH operation or evaluate the feasibility of different types of DFH at their site, by predicting its heating efficiency and air exchange requirement to remove additional water vapor produced by heater.

Objectives:

- Develop DFH heating efficiency model
- Field evaluate heating efficiencies of DFH and IFH

3. Materials and Methods

Model

- A general **water mass balance model** (Figure 1) was developed to estimate air exchange requirement for water removal due to heater combustion. The model was simplified by assuming no occurrence of free surface water, plants, condensation and infiltration because of their relative small effects on water balance.

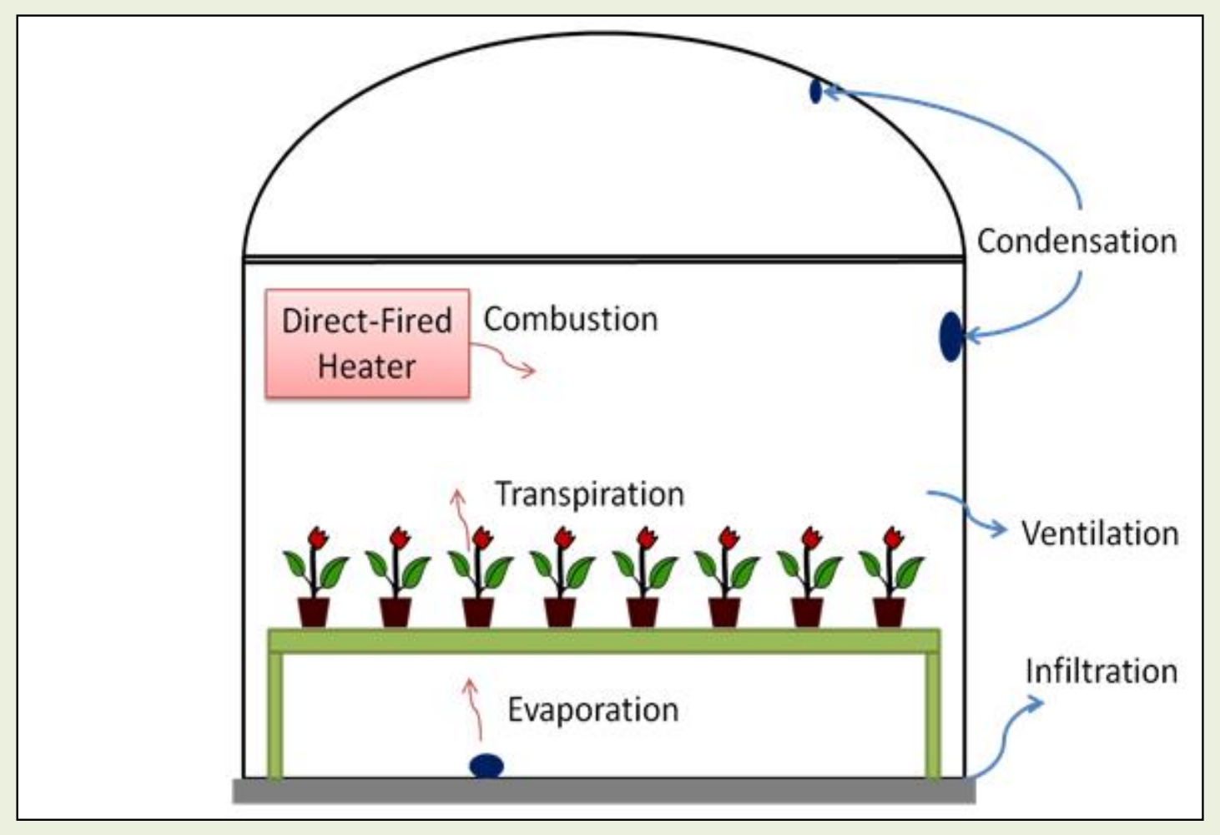


Figure 1: A diagram of the overall process of a water mass balance in a greenhouse air. Waters contributing into the air are combustion, transpiration, and evaporation. Waters leaving the air are condensation, ventilation, and infiltration.

3. Materials and Methods (cont.)

- Besides, an **energy balance model** was used for heating requirement (heat loss) prediction:

Heat Accumulation = Heat Gain – Heat Loss

When greenhouse was maintained at certain temperature, there would be no heat accumulation. Heat loss calculation was adopted from Lee et al. (2010) which can predict heat loss based on greenhouse characteristics, indoor and outdoor meteorological data. Also, heat gain by a propane DFH was estimated using lower heating value (LHV), i.e.: 1937.8 Btu/mole, of following chemical formula:

$$C_3H_8 + 5\ O_2 \rightarrow 3\ CO_2 + 4\ H_2O + Heat$$

- Using above models, a tool as shown in Figure 3 was developed to predict a DFH air exchange requirement and heating performance.

$$Efficiency = \frac{Heating\ Requirement}{Heating\ Requirement + Dehumidification\ Requirement}$$

Experimental Design

- Experiments were carried out in two identical side-by-side, double-poly greenhouses located at Wooster, Ohio (latitude 41°; longitude -82°), where both greenhouses were examined to have similar temperature, relative humidity, and infiltration profile beforehand. The experimental setup and structure characteristics were shown in Figure 2.

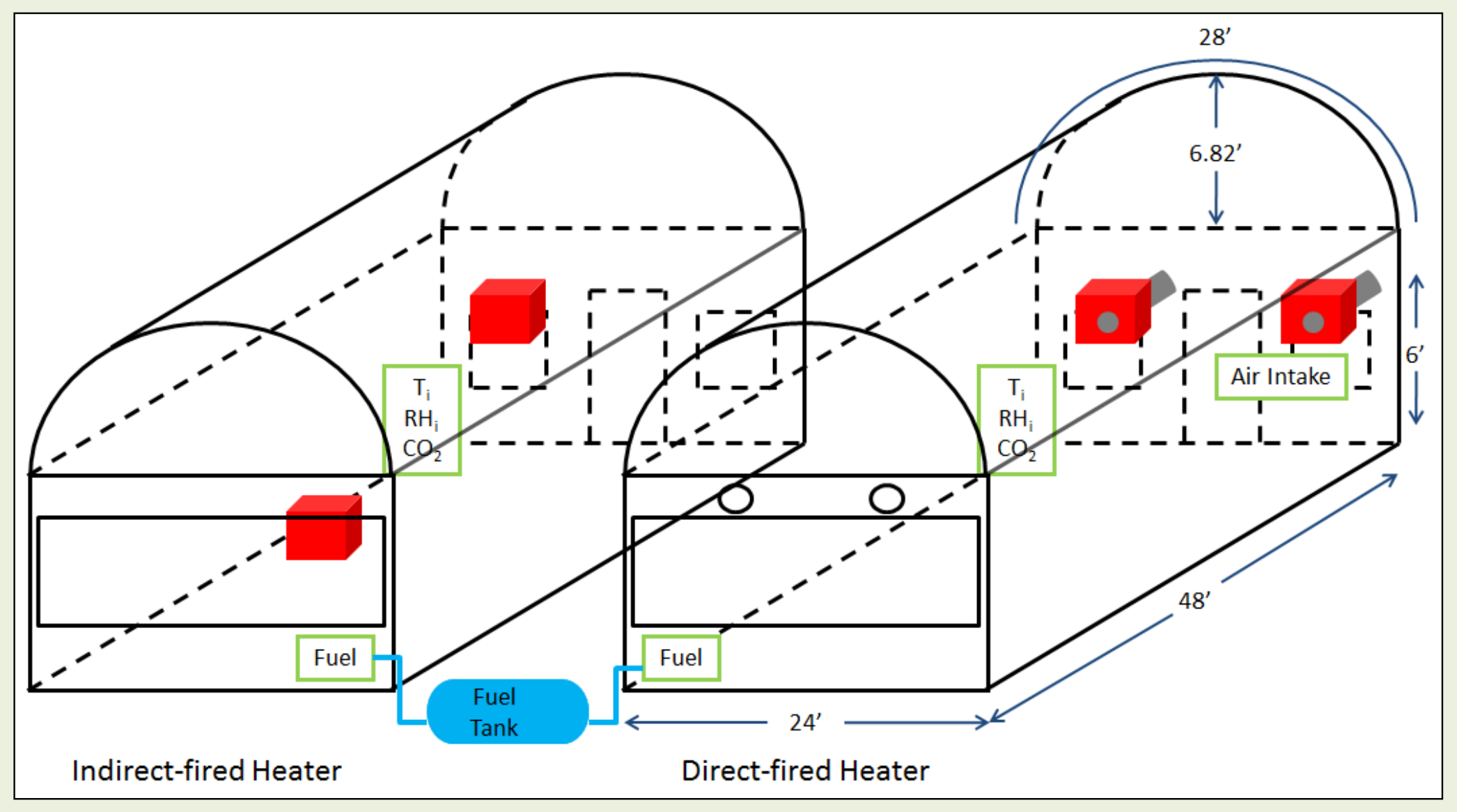


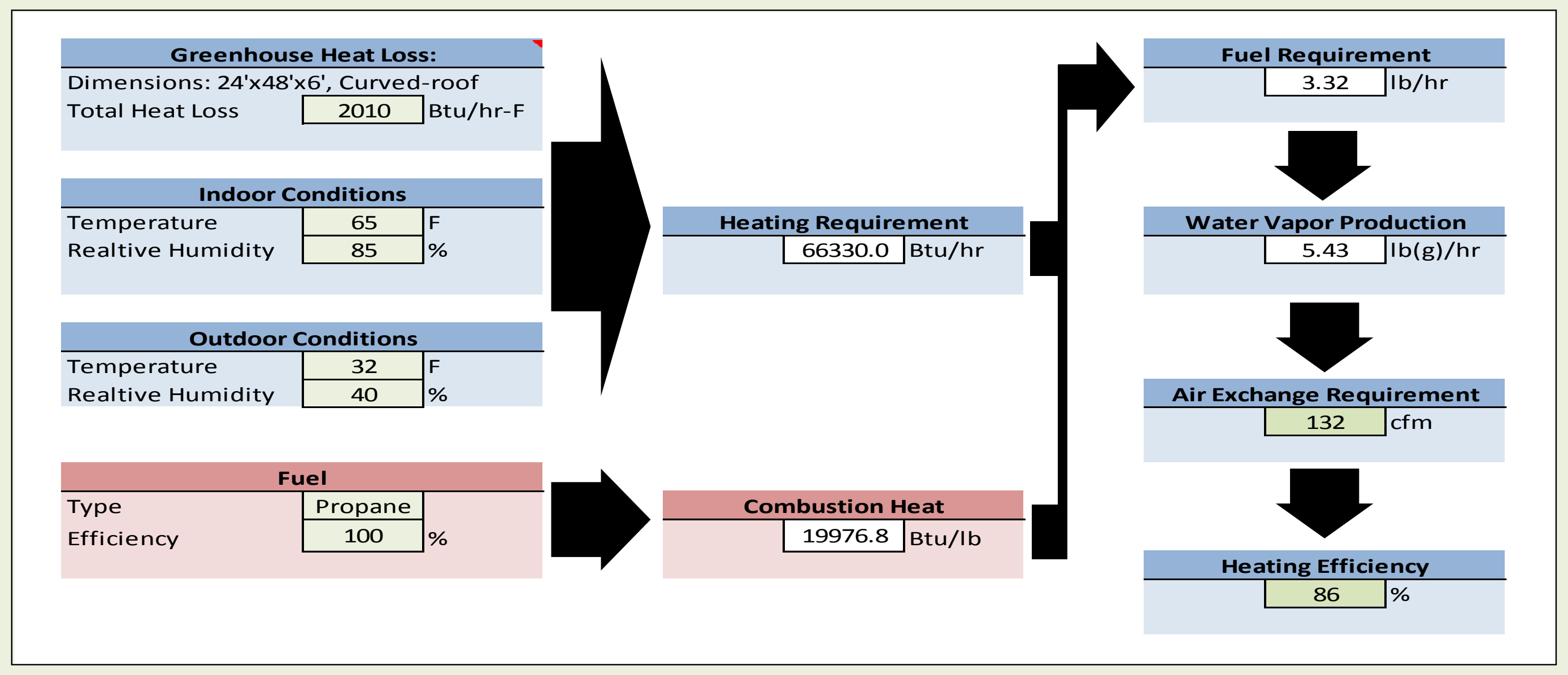
Figure 2: Major sensor and equipment setups in direct-fired and indirect-fired greenhouses. Green outlined boxes were sensors. Red boxes, small circles, squares, and long rectangle symbolized heaters, air exhaust openings, ventilation fans, and cooling pads, respectively.

- Experiment 1 was run about 9 weeks with modification from 2-stage heating to 1-stage heating during the experiment period, and with one fixed air intake rate at 300 cfm.
- Experiment 2 was run about 6 weeks with 1-stage heating and air intake rate was reduced to 200 cfm.

4. Results

- Figure 3 showed the resulting interface of the developed tool, where the result of interest was the air exchange requirement and DFH heating efficiency. A preliminary analysis from this tool showed that a 1-hour event with 33 °F and 45 % differences in temperature and relative humidity, respectively, could reduce the heating efficiency to 86% due to additional 132 cfm air exchange to purge the water vapor.
- Figure 4 showed that DFH efficiency changed depending on temperature and RH difference between indoor and outdoor. An estimation of other efficiencies at different conditions can be done through linear interpolation as $R^2 \approx 1$.
- Figure 5 showed that DFH had lower efficiency with increasing air intake rate. The efficiency was negatively linear to air intake rate as shown (as $R^2 \approx 1$).

4. Results (Cont.)


Greenhouse Heat Loss:
Dimensions: 24'x48'x6', Curved-roof
Total Heat Loss 2010 Btu/hr-F

Indoor Conditions
Temperature 65 F
Realtive Humidity 85 %

Outdoor Conditions
Temperature 32 F
Realtive Humidity 40 %

Fuel
Type Propane
Efficiency 100 %

Heating Requirement
66330.0 Btu/hr

Combustion Heat
19976.8 Btu/lb

Fuel Requirement
3.32 lb/hr

Water Vapor Production
5.43 lb(g)/hr

Air Exchange Requirement
132 cfm

Heating Efficiency
86 %

Figure 3: A diagram of the overall computational process of the heating efficiency and air exchange requirement due to removal of water vapor produced by DFH. DFH combustion efficiency was assumed to be 100%.

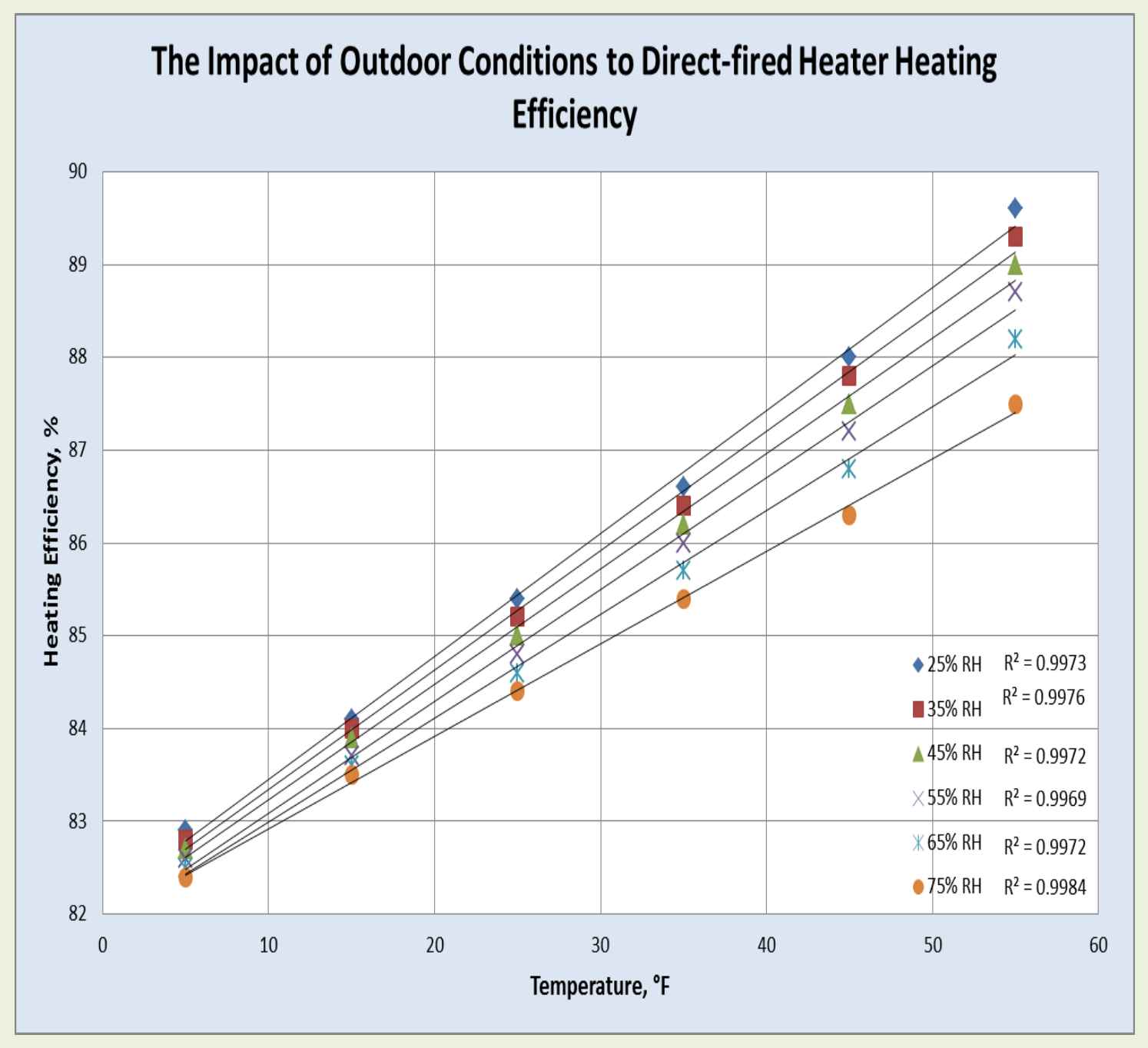


Figure 4: A simulated DFH heating efficiency versus outdoor temperature and RH. Lower the temperature and higher the RH difference is, higher the efficiency is. (Indoor: 65 °F, 85% RH)

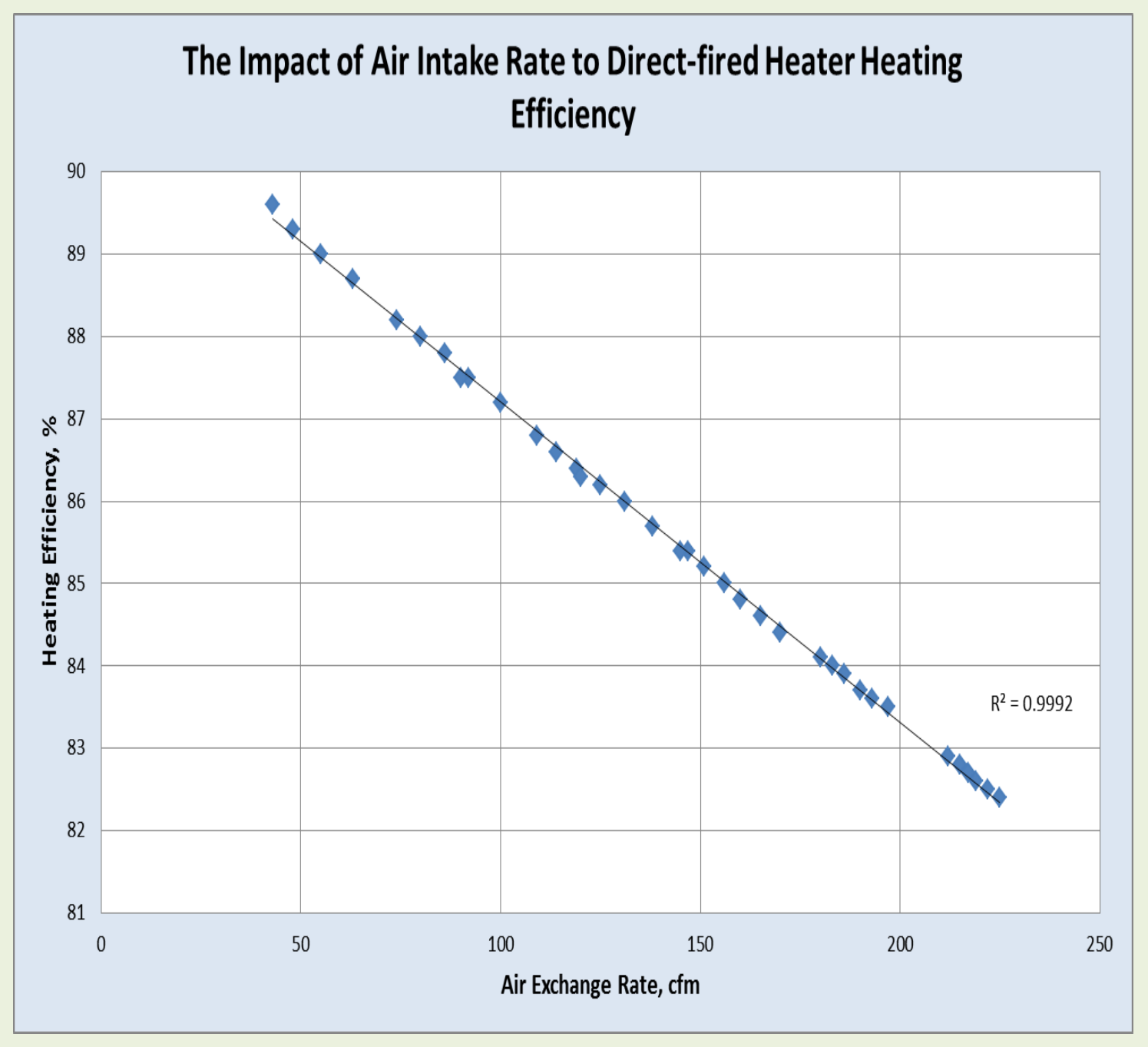


Figure 5: A simulated DFH heating efficiency versus air intake rate. Higher the air intake rate, lower the efficiency is. (Indoor: 65 °F, 85% RH)

- On-site Experiment 1 showed that DFH consumed at least 30% more fuel than IFH with 300 cfm factory-designed air intake, and the RH in DFH greenhouse was 2.6% lower. This indicated that DFH greenhouse was over-dehumidified by its high air intake.
- Experiment 2 showed that 1/3 air intake reduction increased DFH heating efficiency as the result indicated DFH consumed 8.8% less fuel than IFH. The IFH was rated as 80% efficiency heater, which gave a result of 87% heating efficiency to DFH.
- Figure 5 predicted 83.3% heating efficiency for this DFH at 200 cfm, which was 3.7% off from field data.

5. Conclusions and Discussion

- This decision support tool would help in evaluating heating performance and air intake needs for different DFH. Also, growers can use this tool to assess the feasibility of specific DFH according to their greenhouses' characteristics and site conditions, or use it to optimize their current DFH air intake rate.
- The result showed that DFH efficiency was reduced due to air intake need. However, with proper air intake adjustment, the DFH could still be more efficient than conventional IFH.
- Dynamic air intake is desirable as heating efficiency and air intake rate vary at different temperature and RH. Otherwise, a fixed rate at worse case scenario should be chosen.

Reference:

Lee, W. F.(2010). Cooling Capacity Assessment of Semi-closed Greenhouses. MS Thesis. Columbus, Ohio: The Ohio State University.

Jolliet, O. (1994). HORTITRANS, a model for Predicting and Optimizing Humidity and Transpiration in Greenhouses. Journal of Agricultural Engineering Research, 57, 23-37.

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