4-6-2017

Experimental Evaluation of Cooling Effectiveness and Water Conservation in a Poultry House Using Flow Blurring® Atomizers

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Experimental Evaluation of Cooling Effectiveness and Water Conservation in a Poultry House Using Flow Blurring® Atomizers

by

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A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
Department of Mechanical Engineering
College of Engineering
University of South Florida

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Date of Approval:
March 10, 2017

Keywords: Air Assisted Nozzle, Broiler, Evaporative, Spray, Humidity Control

Dedication

This work is dedicated to my wife Sandra, my son Alex, and my daughters Jessica and Veronica, whose infinite patience, constant motivation and faith in me made it possible.

Acknowledgment

First and above all, I want to thank God for giving me so many blessings and surrounding me with the countless individuals that accompanied me during this journey. I want to begin with acknowledging Dr. Rasim Guldiken. Dr. Guldiken has been an amazing mentor not only in an academic aspect, where he excels, but also as a human being. Our collaboration sessions always started, not with research topics, but rather with a "How are you, how is the family, how is work? He understood well where I was coming from, and where I needed to be. He also knew when to push me, to get better and stay on track. Dr. Guldiken, thank you for your numerous suggestions and criticisms, it has been a pleasure to work with you. Dr. Guldiken also introduced me to another person that helped me greatly in this journey; his name Bernard Batson. Mr. Batson was instrumental and provided me with key tools and aids to support this journey.

Next I want to recognize Dr. Alfonso Gañan-Calvo. Dr. Gañan-Calvo has been an inspiration since the day I first spoke with him over the phone. Dr. Gañan-Calvo motivated me to look further into research, during the many intellectual conversations we had during my work visits to Seville, Spain. Alfonso, ¡Muchas Gracias!

I will like to acknowledge the members of my committee Dr. Jose Porteiro, Dr. Nathan Crane, Dr. Aydin Sunol and Dr. Jing Wang, since without their unselfish support this journey will not become a reality.

I will also like to acknowledge Mr. Charlie Hart, Mr. John Marshall and their wives Julia and Sandy, for supporting me throughout the testing and data collection phase of this research project. In addition, I want to thank Dr. Mike Link, who required me to think about my

dissertation, while playing beach volleyball on Saturdays, and has been a positive voice throughout this whole process.

Also to the Embry-Riddle Aeronautical University family, especially Dr. Charles Reinholtz and Dean Maj Mirmirani. Your support throughout the years has been invaluable for me to get here. This work is also dedicated to all the students that continually asked: Mr. Rodriguez, when can we call you Dr.?

To my parents Rafael & Carmen Rodríguez, my sister Carmen Rosado, my brothers Francisco Rodríguez and Manuel Rodríguez. To my Father and mother in-law Ismael and Adela Aldrich.

Last but not least, to my biggest fan, supporter and the love of my life, my wife Sandra. You encouraged me embarked in this journey and have been walking next to me all along. Thank you for all the moments when I needed to be reminded, “You can do it!”

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Abstract

Increases in population as well as economic improvements in developing countries are generating a larger demand for animal protein products. Current animal growth processes inherently, require the use of water in many forms throughout the growth cycle. Water is the most important natural resource on earth to sustain life, and in many developing countries is a scarce resource that must be used wisely. Studies have revealed that poultry growth can take place with less water consumption, when compared with other sources of animal protein (e.g. cattle, pork). In this research, an evaporative Flow Blurring® cooling system was considered as an alternative method for cooling in a full scale poultry (e.g., chicken) farm located near Fayetteville, Arkansas, USA.

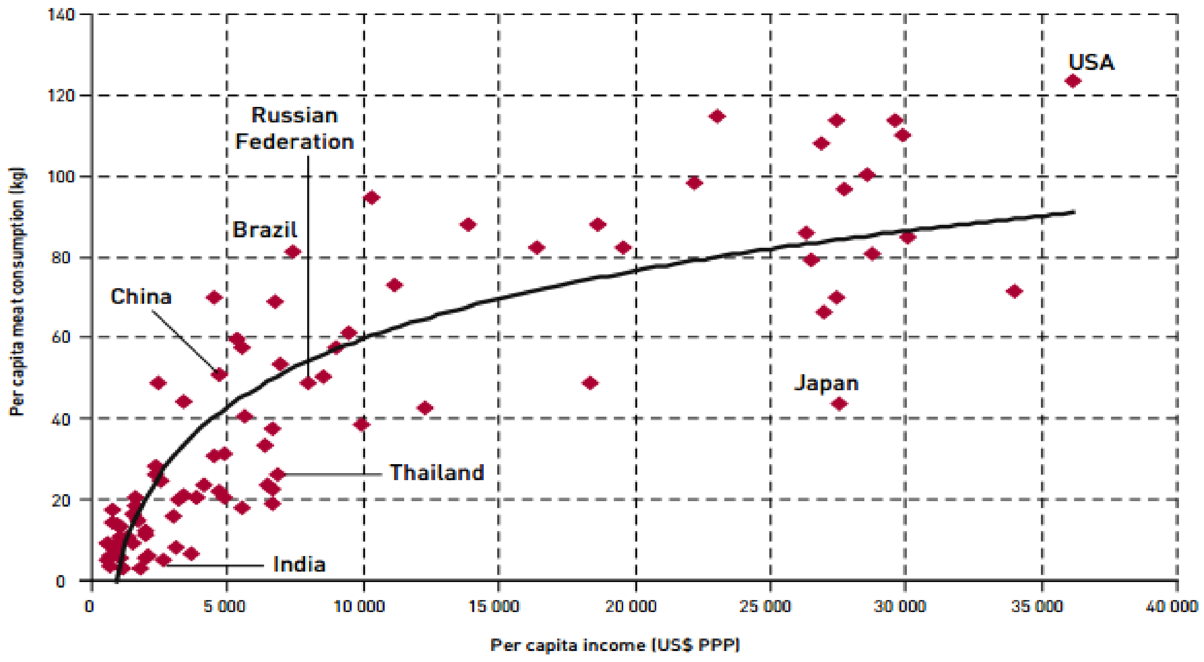
Flow Blurring® is a very efficient pneumatic atomization process, currently used in evaporative cooling consumer products, chemistry instrumentation/analysis equipment, and in combustion investigations. In this dissertation, the Flow Blurring® cooling system was designed, manufactured, installed, and experimentally investigated. A custom control system (i.e., controls logic) was developed to run the sequence of actions required during the operation. Experimental results from the Flow Blurring® cooling system were compared to an existing Cool-Pad evaporative system the current standard in the poultry industry.

The implementation of this new evaporative cooling system resulted in a reduction of approximately 78% in water consumption (10,443 gallons) used for cooling, while the Flow Blurring® cooling system and Cool-Pad systems were concurrently in operation. The Flow Blurring® cooling system maintained comparable and/or enhanced environmental conditions (i.e.

temperature and humidity). Power consumption was higher by 13% when compared to the existing cooling system. The results demonstrate the potential application of a Flow Blurring® cooling system in the poultry agricultural field.

Chapter 1: Introduction

Population and economic growth in developing countries are creating a global demand for food of animal origin (i.e. animal protein). From the early 1970s to the mid-1990s, consumption of meat in developing countries grew by 70 million metric tons, whereas consumption in developed countries grew by only 26 million metric tons [1]. This consumption pattern and improved economies may provide indications of where animal protein intake can increase in developing countries. Figure 1 illustrates this trend as described by Steinfeld [2] for developed and developing countries.



Note: National per capita based on purchasing power parity (PPP).
Source: World Bank (2006) and FAO (2006b).

Figure 1. Relationship between meat consumption and per capita income 2002 [2]. From Livestock's long shadow: environmental issues and options, by Fao, R.L.E., et al., 2006, Reprinted with permission.

One important aspect in most animal protein production process is the demanding use of water for animal hydration, environmental control, and sanitation. As is well-documented, water is a limited resource with no substitute. Life on planet earth depends on it. Vast amounts of financial assets are spent searching for this valuable resource in other planets to prove the existence of life as we know it. As water quantity and quality becomes scarce, mitigation strategies will need to be implemented. People often look for a single answer to a problem; however many partial solutions can add up to a significant solution.

As animal product demand increases, water usage increases proportionally. Mekonnen and Hoekstra [3] reported the volume of water per ton of product (i.e. animal protein) for four different countries as well as global average (Table 1). One can observe from Table 1 that the global weighted average use of water for chicken meat is about 72% that of pig meat (4325 m^3/ton vs. 5988 m^3/ton) and 25% that of beef (4,325 m^3/ton vs. 15,415 m^3/ton).

The dependency on water will be the focus of this research, especially how can we reduce the percentage of service water consumed during the animal protein production. Service water consumption refers to the water used to clean the production site, wash the animals and carry out other services necessary to maintain the environment [3]. Within the service water category, this dissertation will concentrate on the consumption of water necessary to maintain an efficient growth environment. This result must be achieved without affecting the three environmental variables required for an efficient protein production process, namely temperature, humidity, and ventilation.

Table 1. The Green, Blue and Grey water footprint of animal products for selected countries and the weighted global average (m^3/ton) [3]

Animal products	Farming system	China			India			Netherlands			USA			Weighted average			
		Green	Blue	Grey	Green	Blue	Grey	Green	Blue	Grey	Green	Blue	Grey	Green	Blue	Grey	Total
Beef	Grazing	16,140	213	0	25,913	242	0				19,102	525	590	21,121	465	243	21,829
	Mixed	13,227	339	103	16,192	533	144	10,319	761	664	12,726	546	768	14,803	508	401	15,712
	Industrial	10,922	933	1,234	12,412	1,471	866	3,934	349	225	2,949	356	551	8,849	683	712	10,244
	Weighted average	12,795	495	398	15,537	722	288	5,684	484	345	12,933	525	733	14,414	550	451	15,415
Sheep meat	Grazing	9,606	388	0	11,441	489	0				11,910	312	18	15,870	421	20	16,311
	Mixed	5,337	454	14	7,528	582	316	8,248	422	35	9,842	318	74	7,784	484	67	8,335
	Industrial	2,366	451	22	4,523	593	484				0	0	0	4,607	800	216	5,623
	Weighted average	5,347	452	14	7,416	582	314	8,248	422	35	10,948	315	44	9,813	522	76	10,412
Goat meat	Grazing	5,073	272	0	8,081	374	0							9,277	285	0	9,562
	Mixed	2,765	283	0	4,544	381	9	2,443	453	4				4,691	313	4	5,007
	Industrial	1,187	437	0	2,046	436	30							2,431	413	18	2,863
	Weighted average	2,958	312	0	4,194	393	13	2,443	454	4				5,185	330	6	5,521
Pig meat	Grazing	11,134	205	738	3,732	391	325	4,048	479	587	5,118	870	890	7,660	431	632	8,724
	Mixed	5,401	356	542	4,068	893	390	3,653	306	451	4,953	743	916	5,210	435	582	6,226
	Industrial	3,477	538	925	9,236	2,014	1,021	3,776	236	427	3,404	563	634	4,050	487	687	5,225
	Weighted average	5,050	405	648	5,415	1,191	554	3,723	268	438	4,102	645	761	4,907	459	622	5,988
Chicken meat	Grazing	4,695	448	1,414	11,993	1,536	1,369	2,535	113	271	2,836	294	497	7,919	734	718	9,370
	Mixed	3,005	297	905	7,676	995	876	1,509	76	161	1,688	183	296	4,065	348	574	4,987
	Industrial	1,940	195	584	3,787	496	432	1,548	77	165	1,731	187	303	2,337	210	325	2,873
	Weighted average	2,836	281	854	6,726	873	768	1,545	77	165	1,728	187	303	3,545	313	467	4,325
Egg	Grazing	3,952	375	1,189	10,604	1,360	1,176	1,695	76	161	1,740	183	331	6,781	418	446	7,644
	Mixed	2,351	230	708	6,309	815	699	1,085	51	103	1,113	121	212	3,006	312	545	3,863
	Industrial	2,086	206	628	3,611	472	400	1,187	55	113	1,218	132	232	2,298	205	369	2,872
	Weighted average	2,211	217	666	4,888	635	542	1,175	55	111	1,206	130	230	2,592	244	429	3,265
Milk	Grazing	1,580	106	128	1,185	105	34	572	50	32	1,106	69	89	1,087	56	49	1,191
	Mixed	897	147	213	863	132	65	431	40	23	582	59	88	790	90	76	956
	Industrial							500	43	25	444	61	100	1,027	98	82	1,207
	Weighted average	927	145	210	885	130	63	462	41	25	647	60	89	863	86	72	1,020
Butter	Grazing	8,600	577	696	6,448	572	188	3,111	272	176	6,022	373	482	5,913	305	265	6,484
	Mixed	4,880	799	1,161	4,697	716	352	2,345	218	123	3,169	321	478	4,297	492	415	5,204
	Industrial							2,720	233	136	2,417	330	543	5,591	532	448	6,571
	Weighted average	5,044	789	1,141	4,819	706	341	2,513	224	134	3,519	324	483	4,695	465	393	5,553
Milk powder	Grazing	7,348	493	595	5,510	489	160	2,658	232	151	5,145	319	412	5,052	261	227	5,540
	Mixed	4,169	683	992	4,013	612	301	2,003	186	105	2,708	274	409	3,671	421	354	4,446
	Industrial	0	0	0	0	0	0	2,324	199	116	2,065	282	464	4,777	455	382	5,614
	Weighted average	4,309	674	975	4,117	603	291	2,147	191	114	3,007	277	413	4,011	398	336	4,745

- Notes:
  a. Blue water footprint refers to the volume of surface and ground water consumed as a result of the production of the product.
  b. Green water footprint refers to the rainwater consumed.
  c. Grey water footprint refers to the volume of freshwater that is required to assimilate the load of pollutants.
  d. From A Global Assessment of the Water Footprint of Farm Animal Products. Ecosystems, Mekonnen, M. and A. Hoekstra, 2012 Reprinted with permission.

Poultry producers worldwide use ventilation and evaporative cooling as means to control the environment in poultry houses. Ventilation is important to maintain air quality and temperature control within the poultry house. Ventilation is usually broken down into [4]:

a. Minimum ventilation – the purpose is to bring fresh air into the house and exhaust any stale air (to remove excess moisture and prevent the build-up of harmful gases), while maintaining the requisite in-house air temperature.

b. Intermediate ventilation – the aim of transitional ventilation is to remove the excess heat from the house when the house temperature increases above an ideal set point temperature. Transitional ventilation is a temperature driven process during which ventilation fans stop running on a cycle timer (minimum ventilation) and start running continuously for the temperature control.

c. Tunnel Ventilation – tunnel ventilation should only be used when transitional ventilation is no longer capable of keeping the poultry comfortable (e.g. when the poultry show signs of being too hot). Tunnel ventilation is used in warm to hot weather and usually when the poultry are at least 5-6 weeks old.

Ventilation alone is not enough to maintain a desired temperature in hot climates. During hot weather periods, use of evaporative cooling is essential to sustain a comfortable environment for the animals. Two main evaporative cooling systems have been used in the poultry industry, namely, cooling pads (e.g. Cool Cells) and fogging systems (i.e. water atomization).

Cooling pads operate under the principle of dripping water down through a large porous surface, while air is flowing across the surface into the poultry house. Figure 2 illustrates the air and water flow for an evaporative cooling pad system.

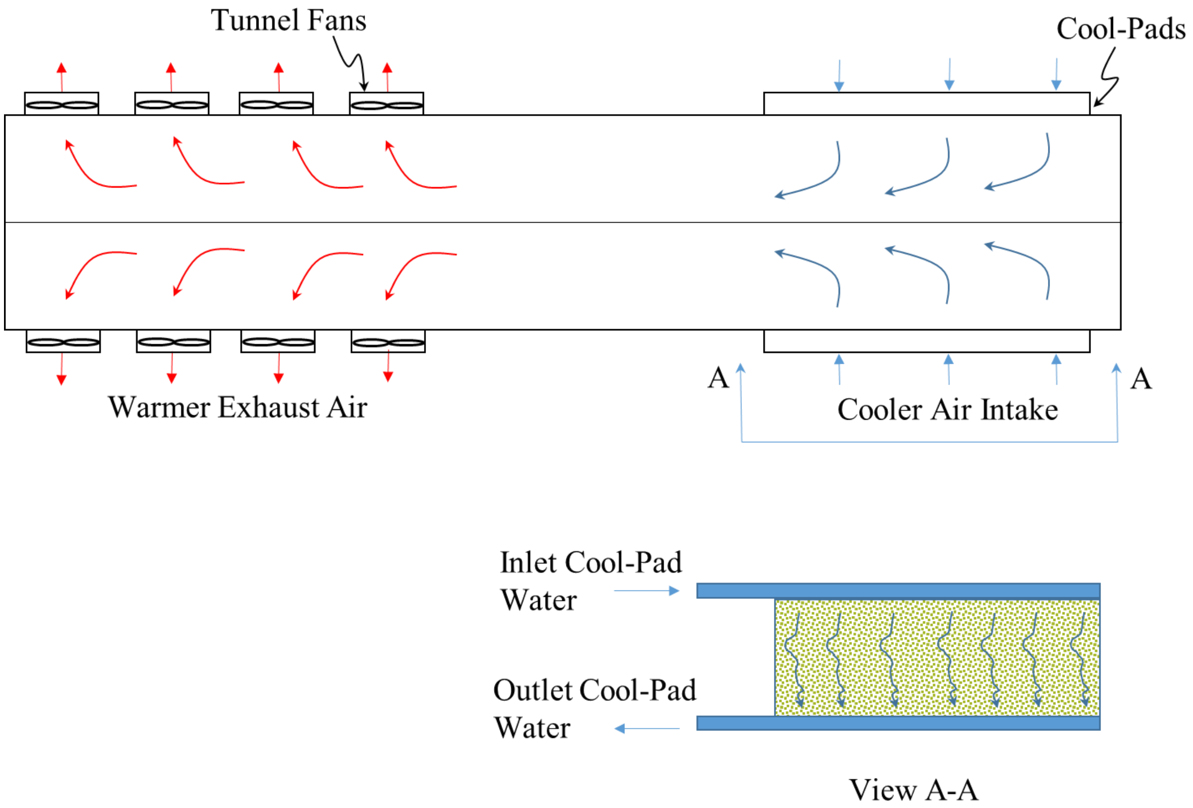


Figure 2. Air and water flow paths for an evaporative cooling pad system

Maintenance of these systems is critical for proper operation. When these systems are maintained properly, they can be effective. Additionally, these systems reduce the risk of directly wetting the interior of the poultry house (e.g. litter).

Fogging systems have been in operation for many years. They operate in the principle of spraying water as small droplets in the fog range (less than 60 µm in diameter) in order to increase the water surface in contact with the air [5]. The small droplets are carried by the air stream in the environment (e.g. poultry houses, outdoor venues, and others) and evaporate by absorbing sensible heat from the air, resulting in a decrease in dry bulb temperature and an increase in air humidity (i.e. percent relative humidity or humidity ratio). The majority of atomizers used today in animal cooling operate under the principle of hydraulic atomization. The primary parameters governing the mean droplet size in this type of atomization process are liquid injection pressure, properties of the liquid (viscosity, density & surface tension), ambient gas (viscosity & density), and atomizer discharge orifice diameter. Figure 3 illustrates the hydraulic atomization process. Although these systems are effective in providing cooling under hot weather conditions, they have been plagued with inconsistent operation.

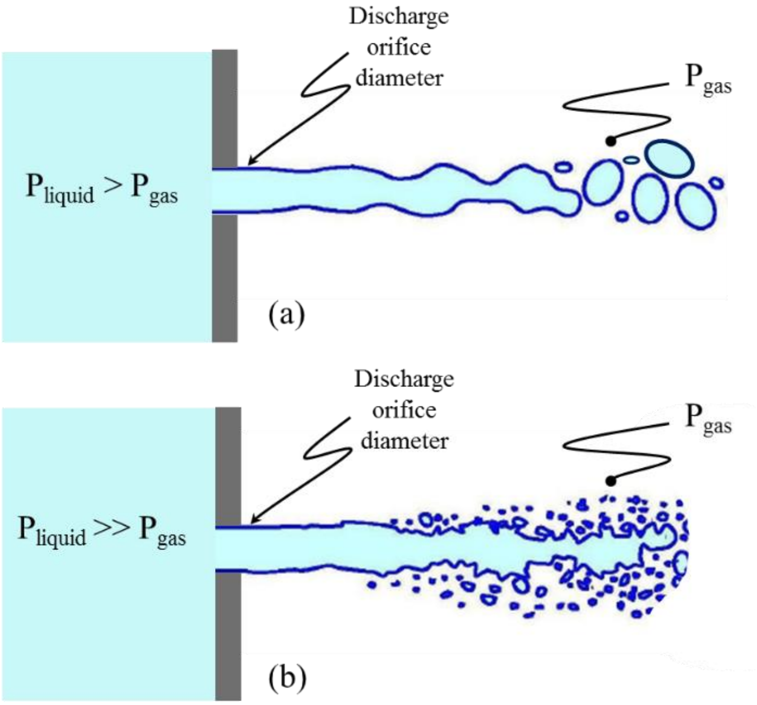


Figure 3. (a) Illustrates the liquid jet breakup at liquid pressure higher than gas pressure; (b) illustrates the liquid breakup at a much higher liquid pressure than the gas pressure.

The main factors causing this unreliable operation are clogging, erosion of the exit orifice and liquid pump wear. Clogging is mainly due the small size of the orifices ranging from 10.6 µm to 25.4 µm (0.004 in to 0.010 in) and dissolved solids and/or water hardness [6]. These issues have been addressed by:

a. Use of inline filters to remove non-dissolved solids equal to or larger than the orifice diameter

b. Use of reverse osmosis (RO) systems, to remove dissolved solids that can accumulate during stagnant system operation.

Although these methods can be effective, the maintenance and implementation (i.e. operational and capital expenses respectively) of these solutions are challenging [7]. Erosion of relatively soft atomizer materials (e.g. polymers, brass, and stainless steel) is addressed using harder materials, such as synthetic sapphire and ruby orifices. However, clogging persists as an undesirable feature, since the orifice size is still very small for proper operation of the atomization process.

Therefore, the contents of this dissertation consist of experimental work of a poultry cooling method using Flow Blurring® (FB®) as the water atomization process to address the aforementioned limitations. In Chapter 2, a detailed description of poultry cooling processes is presented. An overview and literature review on the topics of poultry cooling via natural ventilation, forced ventilation, direct spray, indirect and direct evaporative cooling will be presented.

The principles of operation of a FB® atomizer are considered in Chapter 3. The FB® evaporative cooling is designed to meet the necessary requirements and resources available at the testing site. Following Chapter 3, the test results of the current evaporative cooling system are compared against the FB® evaporative cooling design in Chapter 4.

Finally, general conclusions about the FB® cooling system, recommendations for future research and additional applications in the poultry industry are presented in Chapter 5.

Chapter 2: Poultry Environmental Controls

2.1. Poultry Environmental and Production Controls

Environment control of poultry is a key characteristic of their production growth cycle. Variables like body temperature, feed consumption, growth rate, feed conversion, and mortality depend on other characteristics, including house environmental conditions (e.g. temperature, ventilation, and humidity) [8]. Poultry do not sweat, meaning they must release heat to the environment via sensible and latent heat losses. Body sensible heat loss must be dissipated to the surroundings, mainly through conduction, radiation, and convection heat transfer. Latent heat loss occurs through evaporation of moisture from their respiratory system, as liquid is converted to a gas thru the evaporation process [9]. This latter heat dissipation mechanism is influenced by the humidity in the environment, as discussed later in this chapter.

Havestein [10] documented a significant industry progression in faster growing meat-type chickens. He compared 1957 broilers with 1991 and 2001 broilers (broiler is the name used in the industry for meat type chicken). However, this growth coincided with poorer development of cardiovascular and respiratory systems, contributing to the complications broilers have in managing heat stress. This growth efficiency increase in combination with animal genetics and the potential of global climate change, in turn opening the door for new ways to control the poultry house environment.

2.1.1. Temperature

Temperature (e.g. dry bulb and wet bulb temperatures) is important in the poultry growth cycle, since body heat rejection is a function of this variable, as noted. There are different temperatures of importance in poultry production process. Poultry animals are homeothermic, meaning they produce and dissipate heat to maintain a relatively constant temperature. Adult chickens body temperature varies between 105 °F and 107 °F [11] Body temperature (T_B) is a function of the poultry metabolism, and is of importance in all heat transfer processes. Poultry house indoor temperature (T_{ID}) has an immediate impact on poultry, depending on how well it is monitored and controlled. Anderson [8] documents the temperature that surrounds the poultry and their effects. Table 2 shows the temperature range and their corresponding effects, as documented in [8].

Table 2. Indoor air temperature and poultry heat stress effects [8]

Indoor Air Temperature Range, °C (°F)	**Poultry Heat Stress Effect**
12.8 – 23.9 (55 - 75)	The temperature range in which no metabolic alteration is needed to maintain its body temperature.
18.3 – 23.9 (65 - 75)	Best temperature range.
23.9 – 29.4 (75 - 85)	A small reduction in feed intake can be anticipated.
29.4 – 32.2 (85 - 90)	Feed intake decreases. Cooling processes should be started before reaching these temperatures.
32.2 – 35 (90 - 95)	Feed intake keeps dropping. Heat prostration especially among heavier poultry is possible. Cooling processes must be implemented
35 – 37.7 (95 - 100)	Emergency measures may be needed. Feed intake is harshly reduced. Water intake is really high.
Over 37.7 (100)	Emergency actions are required to increase poultry cooling. Poultry subsistence is the main concern at these temperatures.

The environmental outdoor temperature (T_{OD}) is central, since it influences heat transfer into the poultry house. It also determines when the direct or indirect evaporative cooling system may be utilized effectively. Evaporative cooling systems works best at relatively low outdoor air humidity, which tend to occur during high incidental T_{OD}.

2.1.2. Moisture (Relative Humidity)

The moisture content in the outdoor and indoor air is important in maintaining the proper T_B, since the latent heat rejection depends on this humidity factor. Moisture content can be measured in terms of percent relative humidity or humidity ratio. Relative humidity is defined as the ratio of the partial pressure of water vapor in an air sample, to the partial pressure of saturated moist air sample at the same temperature and pressure [12]

$$\phi = \left. \frac{p_v}{p_g} \right|_{T,P} \tag{1}$$

where ϕ is the relative humidity, p_v is the partial pressure of water vapor at the environment dry-bulb temperature, and p_g represents the saturation pressure of water vapor in the absence of air at the given dry-temperature. This pressure p_g is a function only of temperature, and differs slightly from the vapor pressure of water in saturated moist air. The humidity ratio, on the other hand, is defined as the ratio of the mass of the water vapor to the mass of the dry air [12]

$$\omega = \frac{m_v}{m_a} \tag{2}$$

where ω is the humidity ratio, m_v is the mass of water vapor, and m_a is the mass of dry air. As stated in Section 2.1, the latent heat loss occurs through evaporation of moisture off the poultry respiratory system (e.g. panting process). This evaporation process is dependent on the amount of moisture the air entering the respiratory system can absorb. Air inhaled at a relative humidity of 90% can retain less moisture than air with a relative humidity of 60%, therefore less latent heat rejection can be achieved. Consequently, maintaining a humidity between 40% and 65% is beneficial for poultry in a heat stress scenario [13] [14].

2.1.3. Ventilation

Ventilation of the poultry growth cycle is imperative for two main reasons: (1) the addition and distribution of fresh air to the house/poultry and (2) the modulation of air speed in the poultry house. The need for fresh air comes from the generation of organic and inorganic byproducts, including micro-organisms and harmful gases such as carbon dioxide, nitrous oxides, methane, ammonia and hydrogen sulfide [15]. The modulation of air speed is required for temperature and humidity control. Several methods of ventilation have been utilized to achieve the requirements described above.

a. Natural ventilation – This method relies extensively on natural air motion. To accomplish this process, poultry houses incorporate side curtains. Curtains allow for height adjustment, and provide increase or decrease of airflow area. The house curtains are positioned away from obstructions (i.e. proximity to other buildings), and in the direction of natural air currents. Figure 4 illustrates a naturally ventilated house. Another feature is the addition of circulation fans to promote turbulent air flow around the poultry.

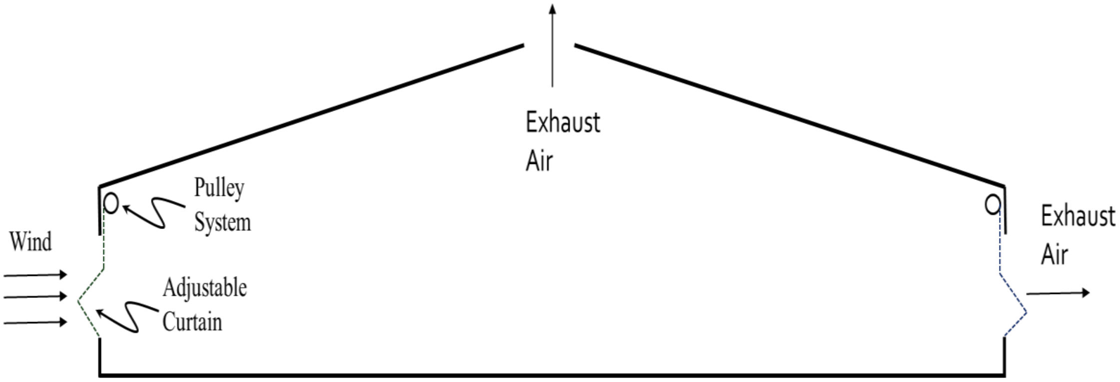


Figure 4. Naturally ventilated poultry house

b. Mechanical ventilation – This method relies on mechanical systems to promote the motion of air into or out of the house. Forced and tunnel ventilation are two processes that can be used to accomplish this outcome. Forced ventilation, uses fans to push fresh air into the house, creating a positive static pressure. Air moves out through exhaust vents. Figure 5 illustrates a forced ventilation system.

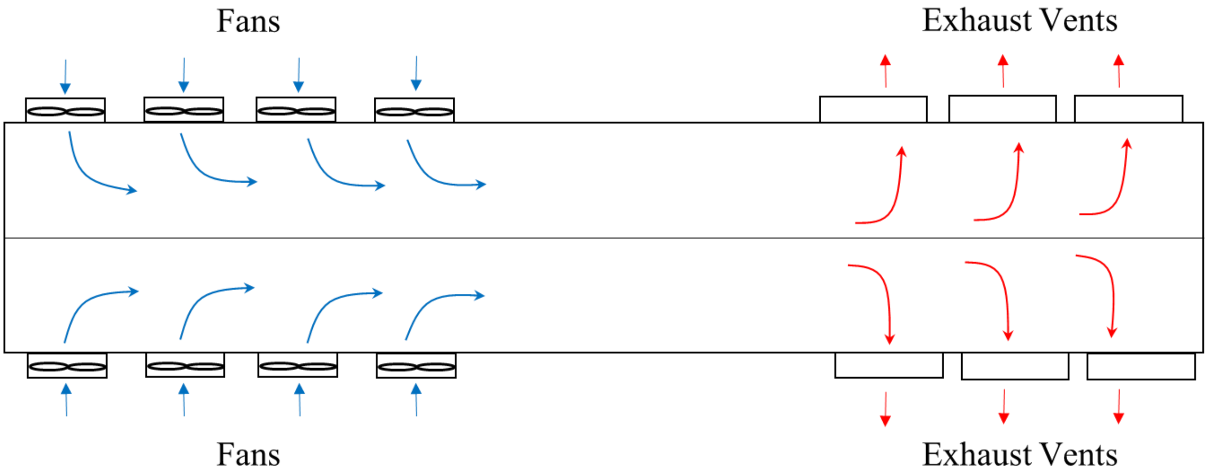


Figure 5. Fans push fresh air into the house generating positive pressure

Tunnel ventilation is another method of mechanical ventilation, and is the preferred ventilation method in the poultry industry today. Its effects were studied decades ago by Drury [16], when he noticed an improvement in poultry weight gain in conjunction with an increase in ventilation air velocity. Additionally, Lott [18] demonstrated improvements in poultry weight gain and feed conversion with increased air velocity. Lacy and Czarick [17] reported similar results in tunnel versus cross-ventilated houses. Timmons and Hillman [19] observed that the sensible and latent heat losses of poultry increase with air velocity. Simmons, Lott, and Miles [20] observed that this air velocity increase was more effective later in the growth process (5-6 weeks old), rather than earlier in the process (3-4 weeks old). Figure 6 illustrates a tunnel ventilation system.

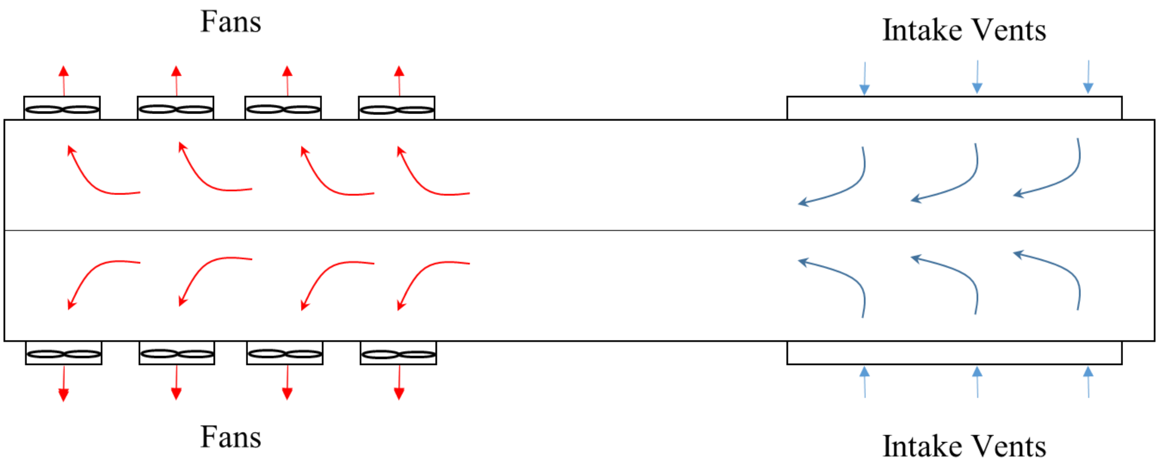


Figure 6. Exhaust fans remove processed air from the house generating negative pressure

2.1.4. Power Consumption

Although both ventilation systems discussed in Section 2.1.3 make use of fans to promote airflow circulation, it is obvious that in terms of power consumption, natural ventilation (NV) is more efficient than the mechanical ventilation (MV) design. This is due to the fans in the NV system working against less flow resistance, as compared to the MV system. On the other hand, MV systems ideally require a sealed and rigid structure to ensure proper operation. This characteristic allows the addition of better insulation systems to prevent the heat gain or loss during summer and winter seasons, respectively. In the winter, this insulation system can reduce power consumption for the heating equipment during the poultry's initial growth process, when the poultry lack feathers to retain the body heat. In the summer, the insulation helps reduce the capacity of alternate cooling systems (e.g. cool-cells and water spray systems)

2.2. Present Cooling Methods

As presented in Section 2.1.3, tunnel ventilation is currently the preferred cooling method in the poultry industry, since it accomplishes many important aspects of the growth cycle at the lowest possible cost. However, this process has its limitations as the outdoor temperature reaches the range of 32.2 °C – 35 °C (90 °F – 95 °F) as seen in Table 2. Supplemental cooling can be achieved by making use of an evaporative cooling process. Evaporative cooling is a process viable in hot climates with relatively low humidity, although it has also been reported the application of these processes in high humidity and temperature environments [21]. The process takes place when non-saturated air is in contact with water. The water will change phase from liquid to vapor, by transferring the heat from the surrounding air. The air temperature drops due to the loss of heat, while absorbing the vaporized water in the process. This process can occur until the air is completely saturated with water (e.g. ϕ (relative humidity) = 100%). Figure 7 illustrates the processes both schematically and on a psychrometric chart.

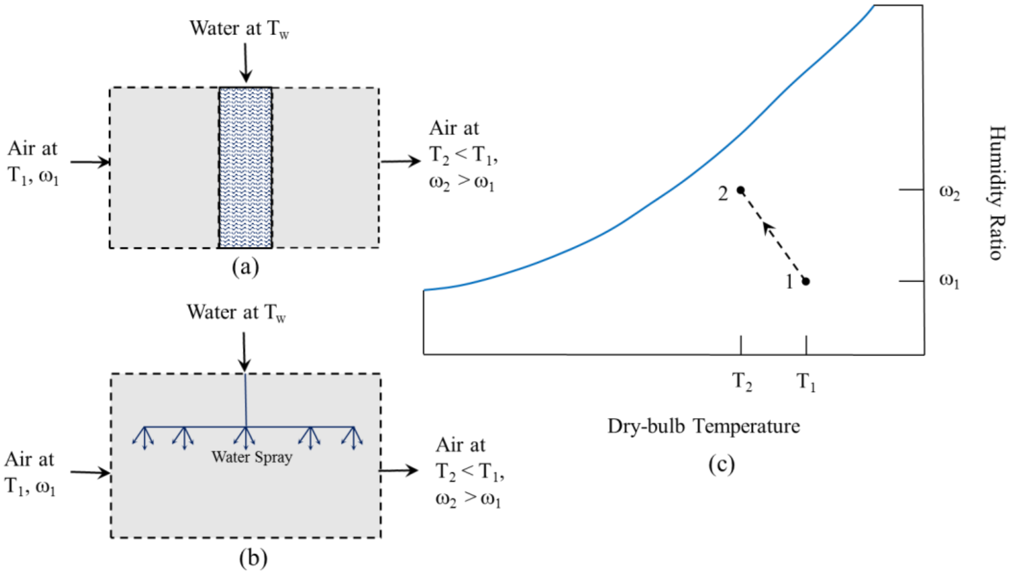


Figure 7. Evaporative cooling processes (a) Cool-Cell equipment diagram, (b) spray (i.e. fogger) equipment diagram, (c) psychrometric chart process representation.

In Figure 7(a) water interacts with air via a large wetted surface to promote the contact area. Figure 7(b) shows the water sprayed into the air. Figure 7(c) illustrates the process 1-2 in a psychrometric chart, where a reduction in dry-bulb temperature occurs ($T_2 < T_1$), as the humidity ratio increases ($\omega_2 > \omega_1$). The maximum reduction in dry-bulb temperature is the difference between incoming dry- and wet-bulb temperatures. When these two temperatures are equal, the air reaches a 100% relative humidity, and the air cannot absorb more moisture. Under these conditions the evaporative cooling process is ineffective. Evaporative cooling effectiveness can then be defined as,

$$\varepsilon = \frac{T_{1,DB} - T_{2,DB}}{T_{1,DB} - T_{1,WB}} \tag{3}$$

where ε is the evaporative cooling effectiveness, $T_{1,DB}$ is the inlet air dry-bulb temperature, $T_{2,DB}$ is the outlet air dry-bulb temperature and $T_{1,WB}$ is the inlet air wet-bulb temperature. Theoretically this effectiveness shall be less than 100%, although these systems can achieve effectiveness between 85% and 95% [22]. Evaporative cooling can be classified into direct and indirect evaporative (DEV and IEV) cooling. Amer, Boukhanouf, and Ibrahim [23] published a detailed review of both DEV and IEV processes, categorizing passive systems that operate naturally with zero power consumption and electrically powered active systems.

2.2.1. Direct Evaporative Cooling Methods

Poultry houses make use of DEV systems, since they are less complex and, simpler to operate. Two DEV's have been used in the poultry industry: cool-cells and fogging systems. Cool-cells, as depicted in Figure 7(a), require a contact media of large surface area to increase the interaction between the incoming air and the water. Currently, these are the preferred DEV system in the poultry industry, since they can provide cooling while maintaining the process water in a confined space. This confinement also limits water contact with electrical equipment and the floor litter (i.e. bedding used in poultry house).

Fogging systems, as they are known in the poultry industry are a type of hydraulic atomization process. This system has been studied in detail for green house cooling and humidity control applications [5, 24, 25]. The use of fogging systems for poultry cooling dates back to the1940's [26]. Their use has declined due to issues described in Chapter 1, and has been replaced with the more approachable cool-cell. One key aspect to point out, is that in almost all the reviewed literature, cooling is correlated to water flow (i.e. quantity of water dispersion), but very few correlations were found in the droplet size of the atomized water (i.e. quality of water dispersion). Most of the fogging systems in the industry utilized for cooling, humidification, dust and odor suppression, and insect control are based on hydraulic atomization at low, medium, or high pressures. Low pressure systems operate at city water pressure within 3.45 to 5.52 bar (50 to 80 psi). These systems produce a relatively large droplet size of approximately 60-50 μm. Medium pressure systems operate at pressures within 6.9 to 13.8 bar (100 to 200 psi). These systems produce a relatively smaller droplet size of approximately 43-30 μm. High pressure systems operate at pressures within 55.2 to 82.8 bar (800 to 1200 psi). These systems produce small droplet size of approximately 15-12 μm. These Saunter Mean Diameter (SMD) droplet sizes are estimated using the correlation shown in equation 4, and developed by Elkotb [27],

$$SMD = (2.25\sigma^{0.25}\mu_L^{0.25}\dot{m}_L^{0.25}\Delta P_L^{-0.5}\rho_A^{-0.25})10^6 \qquad (4)$$

where, *SMD* is the Sauter Mean Diameter in μm, σ is the liquid surface tension in N/m, $\dot{m}_l$ is the mass flowrate in kg/s, ΔP_L is the liquid pressure drop across the orifice in m, and ρ_A is the gas density in kg/m^3.

Pneumatic atomization, is a viable option for a poultry house fogging system. However power consumption of existing pneumatic atomizers are higher than hydraulic atomizers [28], under the same liquid flowrate and droplet size parameters. In the literature review, no research was found where pneumatic atomizers were implemented as a poultry house cooling system, especially Flow Blurring®.

2.2.2. Indirect Evaporative Cooling Methods

As the name indicates, indirect evaporative (IEV) cooling separates the conditioned air from the water evaporation process. The main advantage of this design is the capability for temperature reduction without an increase in humidity. This is primarily accomplished with the implementation of a heat exchanger. One side of the heat exchanger uses a direct evaporative system to cool outside air (i.e. heat sink), while outside air is cooled without an increase in humidity in the other circuit. Figure 8 illustrates an IEV cooling system, with the corresponding psychrometric diagram.

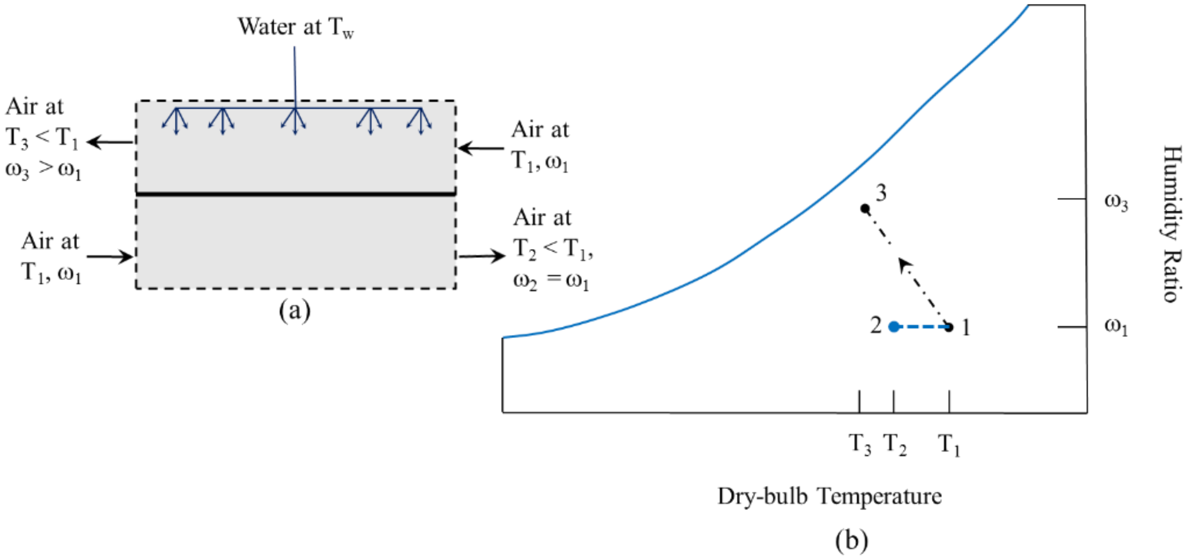


Figure 8. Indirect evaporative cooling processes (a) direct evaporative system/heat exchanger equipment diagram, (b) psychrometric chart process representation.

Although this system can produce the ideal scenario of lower temperature/humidity, it is not a commonly used equipment component in a poultry house. The most probable reason for its exclusion is the cost of the heat exchanger, as it must be large, in order to handle the increased amount of fresh air required for the growth cycle.

2.3. Poultry House Cooling Load

As discussed, poultry house cooling is a necessary component in the poultry growth cycle, especially during hot weather conditions. Another part of this process to be explored is the evolution of the poultry house itself. Current industry house construction is very different, when compared to houses built decades ago [29].Some of today's house size ranges from 40-ft by 400-ft , to 50-ft by 500-ft, contingent on the design poultry density per house. Poultry density decision is mainly based on bird welfare, performance (i.e. feed conversion) and product quality. For example European Union poultry densities are based on the EU Welfare Directive (2007), with limits between 33 kg/m^2 (6.7 lbm/ft2) to 42 kg/m^2 (8.6 lbm/ft2) [30]. Poultry houses are designed with specific purposes based on the location and climate of the region or country. These may range among tropical, desert, temperate and cold regions [31]. Of particular interest is the southeast of the United States (e.g. Georgia, Alabama Arkansas, North Carolina and Mississippi), where this study's research testing occurred. This is one of the highest poultry producing areas in the United States [32], and is classified as a "Cfa" region under the Köpper-Geiger climate classification. This "Cfa" classification is assigned to regions with temperate climate, without dry season (i.e. no dry summer or winter) and having hot summers. These climate regions must provide additional cooling during hot weather periods.

The house designs vary from open-sided high rise cage with side curtains, which rely on natural air flow through the house, to low rise and well insulated forced ventilated buildings. New buildings make use of many home construction design features like dropped ceilings with insulation (typical R19), solid/insulated (typical R11) side walls, heating/cooling systems, hot/cold weather ventilation, LED lighting, electronics controllers, alarms and back-up generators. Every one of these systems is designed and implemented with one purpose in mind, to reduce energy costs and ensure efficient operation of the house.

2.4. Poultry Heat Generation

Poultry heat generation is of primary importance, as their heat generation is the largest load in the poultry house design [33]. As stated earlier, poultry are homeothermic, therefore they most release heat to, or absorb heat from the environment to maintain an even internal body temperature. This released heat can be in the form of sensible and latent heat, via conduction, convection and radiation heat transfer. The amount of heat can be influenced by nutrition, house design, growing practices, and genetics and has increased throughout the years [10]. Several studies have quantified this energy transfer under laboratory controlled conditions or field trials [14, 34-36]. Recently Fairchild and Czarick [33] published an average daily sensible and latent heat production of 16-35 and 28-51 Btu/hr/bird (4.7-10.2 and 8.2-14.9 W/bird) respectively. Assuming a target poultry weight of 6 lbm, the sensible and latent heat rejection can be estimated at 2.7-5.8 Btu/hr/lbm and 4.7-8.5 Btu/hr/lbm respectively.

2.5. Flow Blurring® Background

Flow Blurring® (FB®) is an efficient atomization process that has its roots in the well know Flow Focusing atomization published by Gañan-Calvo [37]. The FB® process was first reported by Gañan-Calvo in 2005 [38], and has been applied in many industries like fuel injection, analytical chemistry, pharmaceutical, biotechnology, cosmetics and agricultural. In the agricultural field, FB® has been applied in humidification of food producing plant (e.g. tomatoes). Specific details of this atomization platform will be covered, in Chapter 3, where a full description and analysis will be presented.

Chapter 3: Design and Testing of a Flow Blurring® Cooling System

This chapter describes the methodology and design of a study, which examined the application of a Flow Blurring® cooling system in a poultry house. Research questions to guide the study are presented. The description of the design methodology addresses the design of the cooling system, including the cooling load, Flow Blurring® atomizer, controls logic and air/water distribution sub-systems. The design was planned to deliver the necessary cooling to a production and testing poultry house facility located near Fayetteville, AR during the period of July-August of 2015. The poultry house is representative of a real production facility and contained 20,000 birds at the start of the growth cycle.

A list of research questions follows:

a. Can a Flow Blurring® atomization system achieve the necessary cooling and humidity control in a poultry house, and reduce the water consumption during this process?
b. Can this systems allowed the growth of protein in locations where water is a prime resource?

3.1. Poultry House Cooling Load

The performance of the environmental control system in a poultry house depends on many variables. The cooling load (i.e. heat gain) is one important variable in the selection and sizing of a cooling system. The cooling load can be broken down as illustrated in Figure 9.

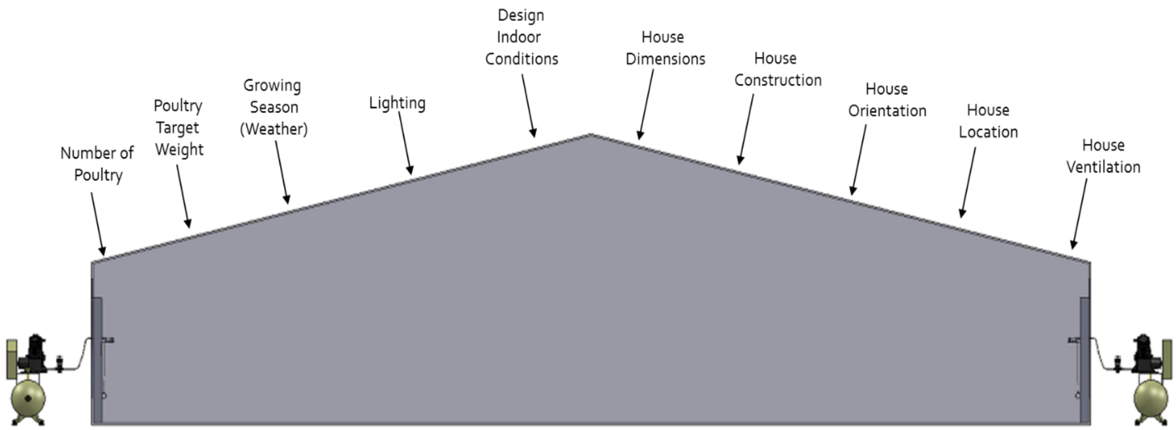


Figure 9. Poultry house cooling load variables

A detailed description of the items in Figure 9 is as follows.

3.1.1. Poultry House Location, Orientation and Construction

The poultry houses for this research are part of the University of Arkansas–Division of Agriculture, located in Fayetteville, Arkansas. As shown in Figure 10, house number 3 was used as the control group for the Environmental Control System (ECS) research. The ECS for house number 4 was modified to incorporate the proposed Flow Blurring® cooling system (FBCM). The shorter walls of the poultry houses have been oriented east-west, to reduce the solar irradiation exposure. The houses were also separated by a distance of 23 meter (approximately 75 ft), to prevent cross-house ventilation intrusion.

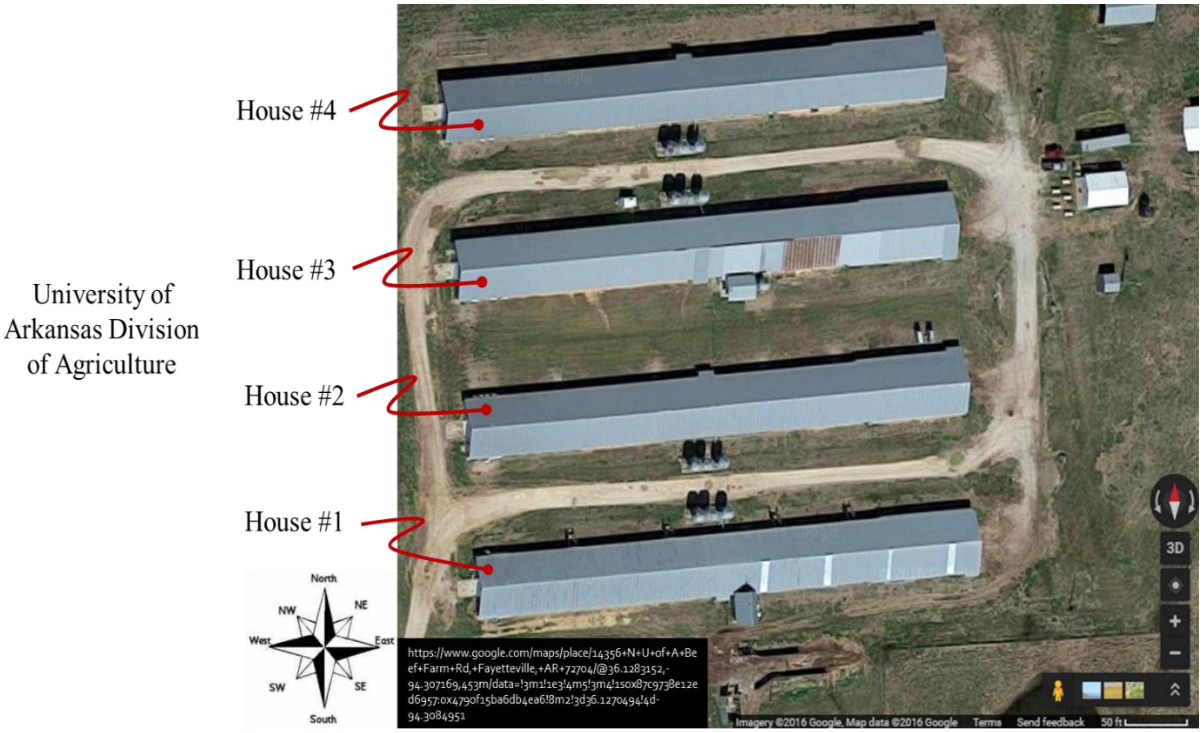


Figure 10. Aerial view and address of research facility site

Table 3 illustrates the house dimensions and construction details that were used in the heat gain calculations.

Table 3. Poultry house construction information

	House 3 (Control Group)	**House 4 (FB Cooling System)**
Length	122 m (400 ft)	122 m (400 ft)
Width	12.2 m (40 ft)	12.2 m (40 ft)
Peak	3.30 m (10.8 ft)	3.23 m (10.6 ft)
Side Wall	1.83 m (6 ft)	1.80 m (5.92 ft)
Structure	Wooden Trusses	Wooden Trusses
Ceiling Insulation	R-19 (19 ft^2 °F hr /BTU)	R-19 (19 ft^2 °F hr /BTU)
Side Wall Insulation	R-11 (11 ft^2 °F hr /BTU)	R-11 (11 ft^2 °F hr /BTU)
Roof	Galvanized Corrugated Sheet metal	Galvanized Corrugated Sheet metal
Ventilated Attic	Yes	Yes
Cool Cell per Side (North and South Sides)	21.34 m x 1.22 m x 15.24 cm (70 ft x 4 ft x 6 in)	21.34 m x 1.22 m x 15.24 cm (70 ft x 4 ft x 6 in)
Electrical Capacity	60 A	60 A
Bedding	Rice Hulls/KD Pine Shavings	Rice Hulls/KD Pine Shavings

Next item in the cooling load analysis is to establish the outdoor design conditions. The ASHRAE Handbook of Fundamentals provides weather data for locations in the United States and worldwide [39]. The test site is located approximately at latitude 36.13 N and longitude 94.31W. The closest location to the test site, is Smith Field, Arkansas at a latitude 36.19 N and longitude 94.48W. The cooling dry-bulb/mean coincident wet-bulb temperatures for this location at 2% are 90.2 ^{o}F and 74.2 ^{o}F respectively. The 2% indicates that there is a probability of 2% that temperatures can be higher than these two values. Using Equation (1) illustrated in section 2.1.2, at an altitude of 363.9 m (1194 ft) at the given temperature, we obtain an outdoor relative humidity of 47.6%. This means that the outdoor air can absorb moisture added by the ECS, and reduce the temperature via the evaporative cooling process discussed in Chapter 2.

The next step in the determination of the cooling load will be to calculate the conduction, convection and radiation heat transfer into the house. Although extensive steady and unsteady state analysis have been performed in similar production environments [40-43], one important aspect must be emphasized. The cooling load of a poultry house depends more on the number of birds in the process, rather than the cooling load on the building on its own. The current research study used 20,000 birds, which a common lot size for the house size. A similar size was used by Xin in 2001 [44]. Czarick [45] developed and provided an open source MS-Excel spreadsheet that can perform a simplified cooling load calculation. A sample of the tool results with specific input data for the test site is shown in. Table 4.

Table 4. House 4 cooling load based on Czarick open source tool

Design Conditions			
Inside Temperature (°F)	80		
Outside temperature (°F)	90.2		
Basic House Information			
House Length (ft)	400		
House Width (ft)	40		
Total Side wall Height (ft)	6		
Peak Height (ft)	10.58		
Open or Dropped Ceiling (o/d)	d		
Poultry Information			
Number of birds	20000		
Heat Generated by bird (Btu's/hr per lbm)	5.8[a]		
Bird weight (lbm)	6		
Side wall construction (for houses without curtains: Curtain height = 0)			
Curtain height	0		
Side wall height - excluding stem wall (ft)	6		
Stem wall height	0		
R-values			
Ceiling R-value	19		
End wall R-Value	11		
Side wall R-value	11		
Stem wall R-value	4		
	Area	Heat Gain	Percent
Ceiling	16,414	39,048	5.2%
End walls	663	615	0.1%
Side walls	4,800	4,451	0.6%
Stem walls	0	0	0.0%
Lights		4,352	0.6%
Birds		696,000	93.5%
	TOTAL	744,466	100%

Notes:

a. The heat generated 5.8 Btu/hr/lbm is taken from the sensible heat estimation in [33]

As one can observe from Table 4 it is estimated that 93.5% of the cooling load (696,000 Btu/hr) is accounted for by the number of birds in the house and only 6.5% (48,466 Btu/hr) is due to the conventional heat transfer modes into the house. Therefore an extensive refinement of conduction, convention and radiation heat transfer loads will only have a minor effect on the total cooling load.

Next we will use the cooling load to estimate the amount of water required to be evaporated, to absorb the total cooling load of 744,466 Btu/hr. For this we will make the assumption that the supply water temperature is approximately 18.3 C (65 ^{o}F). Therefore, making the density of water as 1000 kg/m^3 (62.4 lbm/ft^3) and enthalpy of vaporization as 2457.5 kJ/kg (1056.5 Btu/lbm). Equation 5 was used to calculate the supply water rate.

$$\lambdabar = \left(\frac{60\varphi}{\rho h_{fg}}\right)10^{6} \qquad (5)$$

where, $\lambdabar$ is the volumetric flow rate in ml/min, φ is cooling load in kW, h_{fg} is the enthalpy of vaporization of water in kJ/kg and ρ is the density of water in kg/m^3. Based on Equation (5) and the data above, the required water volumetric flowrate was found to be 5379 ml/min. The initial ECS concept contained four FBCM, therefore each module will handle approximately 1345 ml/min. The water flow to each FB® atomizer is controlled by the use of a 3.85 LPH water dripper manufactured by Rivulis, Gvat, Israel. As a result, the theoretical number of atomizers per module is 21.2, however to keep an even number of atomizers the system was designed to use 20.

3.1.2. Poultry House Ventilation

Both of the houses used during testing had the same ventilation schedule, to provide fresh air and cooling as needed. Table 5 shows the ventilation schedule [46], which supplied power to a specific device based on a temperature difference between the actual indoor temperature and an ideal baseline temperature. The baseline temperature (T_i), was supplied by the poultry house manager, and varies with the age of the birds [46]. Table 6 documents T_i and the corresponding range of relative humidity.

Table 5. Ventilation schedule for poultry houses 3 and 4

Equipment Employed	**On ΔT (°F)**	**Off ΔT (°F)**
Daily Ideal Temperature	T_i	
Exhaust Fan 1	T_i +2	T_i +1
Exhaust Fan 2	T_i +2	T_i +1
Exhaust Fan 3	T_i +2	T_i +1
Exhaust Fan 4	T_i +2	T_i +1
Tunnel Fan 1	T_i +3	T_i +2
Tunnel Fan 2	T_i +4	T_i +3
Tunnel Fan 3	T_i +7.5	T_i +4.5
Tunnel Fan 4	T_i +8	T_i +5
Tunnel Fan 5	T_i +9	T_i +8
Tunnel Fan 6	T_i +10	T_i +9
Cool Pad or FB® system	T_i +11	T_i +10
Tunnel Fan 7	T_i +12	T_i +11
Tunnel Fan 8	T_i +13	T_i +12

Table 6. Indoor design temperature for poultry houses 3 and 4

Growth Cycle	SAVOY Farm Indoor Design Temperature (T_i)	Indoor Design Relative Humidity	
(Days)	(°F)	(%RH MIN)	(%RH MAX)
1	90	45	65
3	90	45	65
7	85	45	65
14	83	45	65
21	80	45	65
28	72	45	65
35	70	45	65
42	68	45	65
49	63	45	65

3.2. Development of a Flow Blurring® Atomizer

3.2.1. Flow Blurring® Droplet Size Calculation

According to Gañán-Calvo [38] a, Flow Blurring® (FB®) atomizer as illustrated in Figure 11, can generate up to fifty times more surface area than any other pneumatic atomizer of the "plain jet type as documented by Lefebvre [4]. This FB® atomizer configuration is obtained by locating a liquid conduit of internal diameter "*D*" concentric with an exit orifice having an equal diameter "*D*", as illustrated in Figure 11. The liquid conduit end is positioned at a distance "*H*" from the exit orifice. A critical parameter indicated in [38] is the H/D ratio that must be equal to or less than 0.25 in order to operate in the FB® regime. The FB® regime is considered as a polydisperse atomization mode. In the case that H/D is higher than 0.25, the atomization falls under a monodisperse mode described by Gañán-Calvo as Flow Focusing (FF) [37].

It is important to note that at the ratio H/D = 0.25, the effective port area (*EPA*) created by the *H* dimension equals the port area of the exit orifice *D*, therefore

$$EPA = \pi DH \tag{6}$$

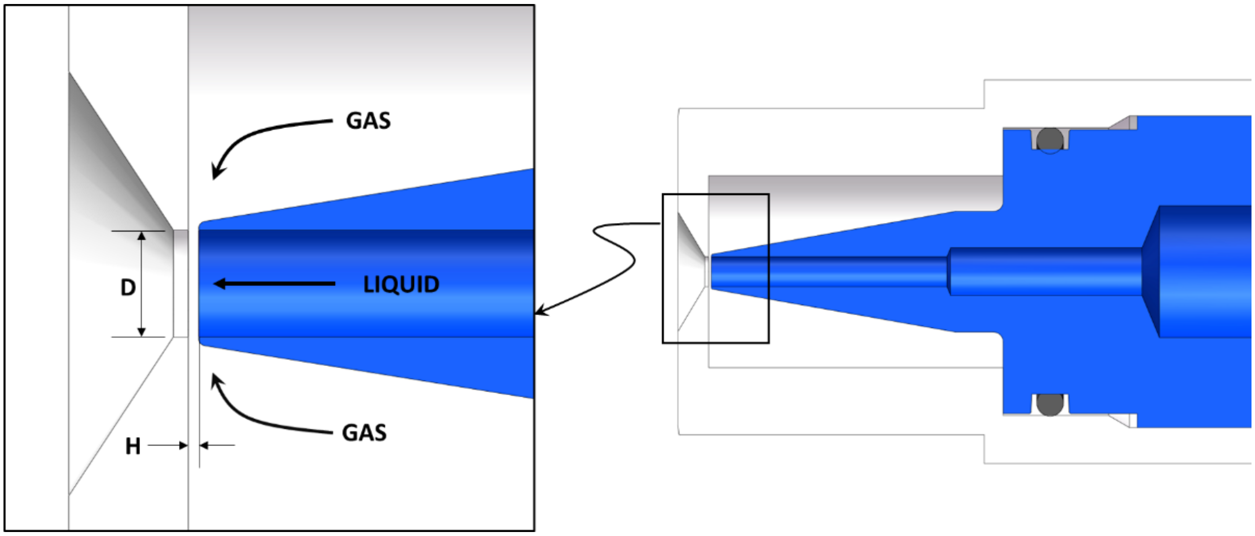


Figure 11. Schematic of simple Flow Blurring® geometry

The characteristic H/D ratio of less than or equal to 0.25 creates a micro-mixing zone without the use of passive or active design features in the atomizer [38]. This geometric parameter generates a backflow pattern and premix mechanism illustrated in Figure 12. This pattern/mechanism allows the FB® atomizer to produce a polydisperse spray with relatively high flowrates of up to 7.2 LPH (1.9 GPH).

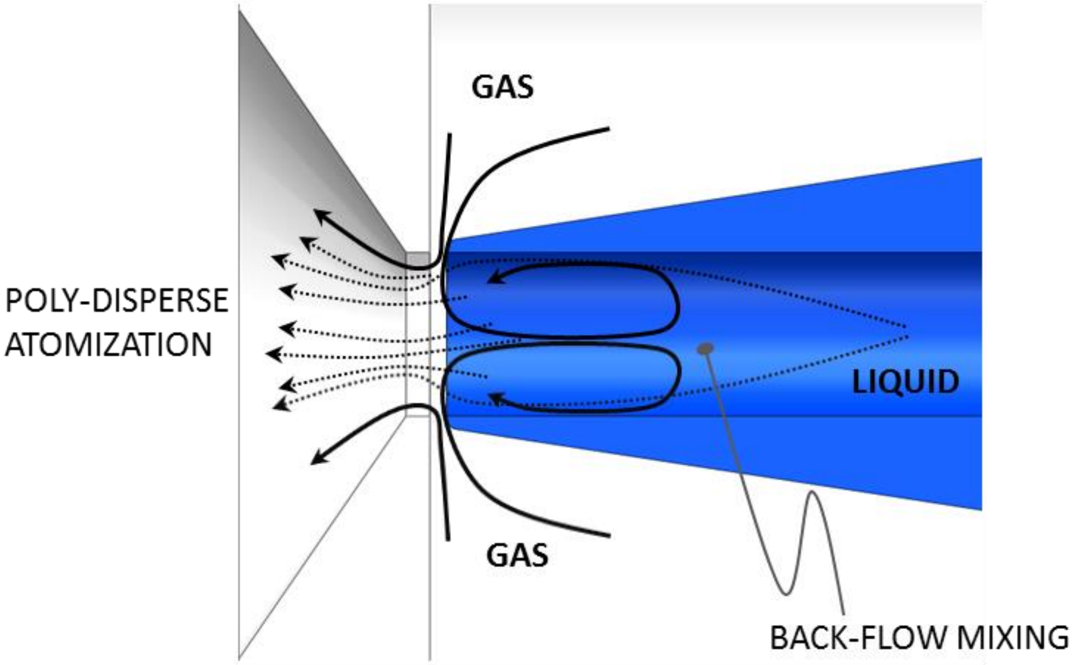


Figure 12. Flow Blurring® back-flow mixing region in the liquid conduit

The dimensionless mass median diameter (MMD) or d_{50} diameter, as is used in practice, is defined as 50% of the total volume of droplets smaller than this diameter [47]. It can be calculated as reported in [38], and shown below,

$$MMD = \delta / D \tag{7}$$

where, D is the FB® atomizer exit orifice in meters and δ is defined by Equation 8 below.

$$\delta = C_1 We_D^{-0.6}(1+C_2 Oh_D)(1+C_3 GLR^{-1})^{1.2} \text{ (dimensionless)} \tag{8}$$

In this equation C_1, C_2 and C_3 are best-fit experimental constants with values of 0.42, 18 and 1 respectively as reported in [38]. We_D is the Weber number, which is a dimensionless number that relates the inertial to surface tension forces at the interface between two different fluids

$$We_D = \frac{\rho_g U_g^2 D}{2\sigma} \tag{9}$$

where, ρ_g is the air density at the atomizer exit pressure drop in Pascal and supply air temperature (°C), U_g is the air exit velocity in meters per second based on the mass flow rate of air through the effective port area, D is the atomizer exit orifice in meters and σ is the water surface tension in newton per meter.

The Ohnesorge number (Oh_D), which is a dimensionless number relating the viscous forces to inertial and surface forces is defined per equation 10

$$Oh_D = \frac{\mu_l}{\sqrt{\rho_l \sigma_l D}} \tag{10}$$

where, μ_l is the water viscosity in pascal-second, ρ_l is the density of water in kilogram/cubic meter, σ_l is the water surface tension in newton per meter and D is the atomizer exit orifice in meters. GLR is the gas to liquid mass flowrate ratio

$$GLR = \frac{\dot{m}_g}{\dot{m}_l} \tag{11}$$

where, $\dot{m}_g$ is the mass flowrate of air and $\dot{m}_l$ is the mass flowrate of water both in kilograms per second.

3.2.2. Flow Blurring® Atomizer Design and Validation

One important feature of the FB® atomization process is that water never contacts the perimeter of the exit orifice (Figure 12), since the air surrounds the water flow through the exit orifice. This feature eliminates or significantly reduces clogging, which is a problem with current spray evaporative cooling systems [48, 49]. The following specifications drove the FB® atomizer development:

Droplet mass median diameter shall be less than 20 μm (target of 3 times smaller than current fogging systems).

a. Atomizer design gas (i.e. air) pressure of less than 206.8 kPa (30 psi).
b. Atomizer design liquid (i.e. water) flowrate shall be approximately 3.80 LPH (1 GPH).
c. Minimize the gas (air consumption) due to limited electrical current capacity (60A per house) at the test site.
d. Liquid (i.e. water) flow control must be achieved while the system operates at different supply pressures (variations in city water pressure).
e. No tools shall be required to remove and replace the atomizer from the system.
f. The atomizer must be easy to disassemble with the use of tools for the purpose of inspection and maintenance.
g. Water and air connectors must be of standard metric sizes.
h. All atomizer materials must be compatible with water and air, in addition to prevent corrosion in a broiler environment (i.e. moisture, dust, feathers, and low concentrations of ammonia).
i. The atomizer shall allow the assembly of a network of atomizers in series and/or parallel configurations.

Analysis of several design cases was performed, using the equations listed in the previous section and the specification above. Table 7 reflects the input parameters and Table 8 reflects the results for five different cases. Case number five (5) met all the performance criteria and was used as the baseline design criteria.

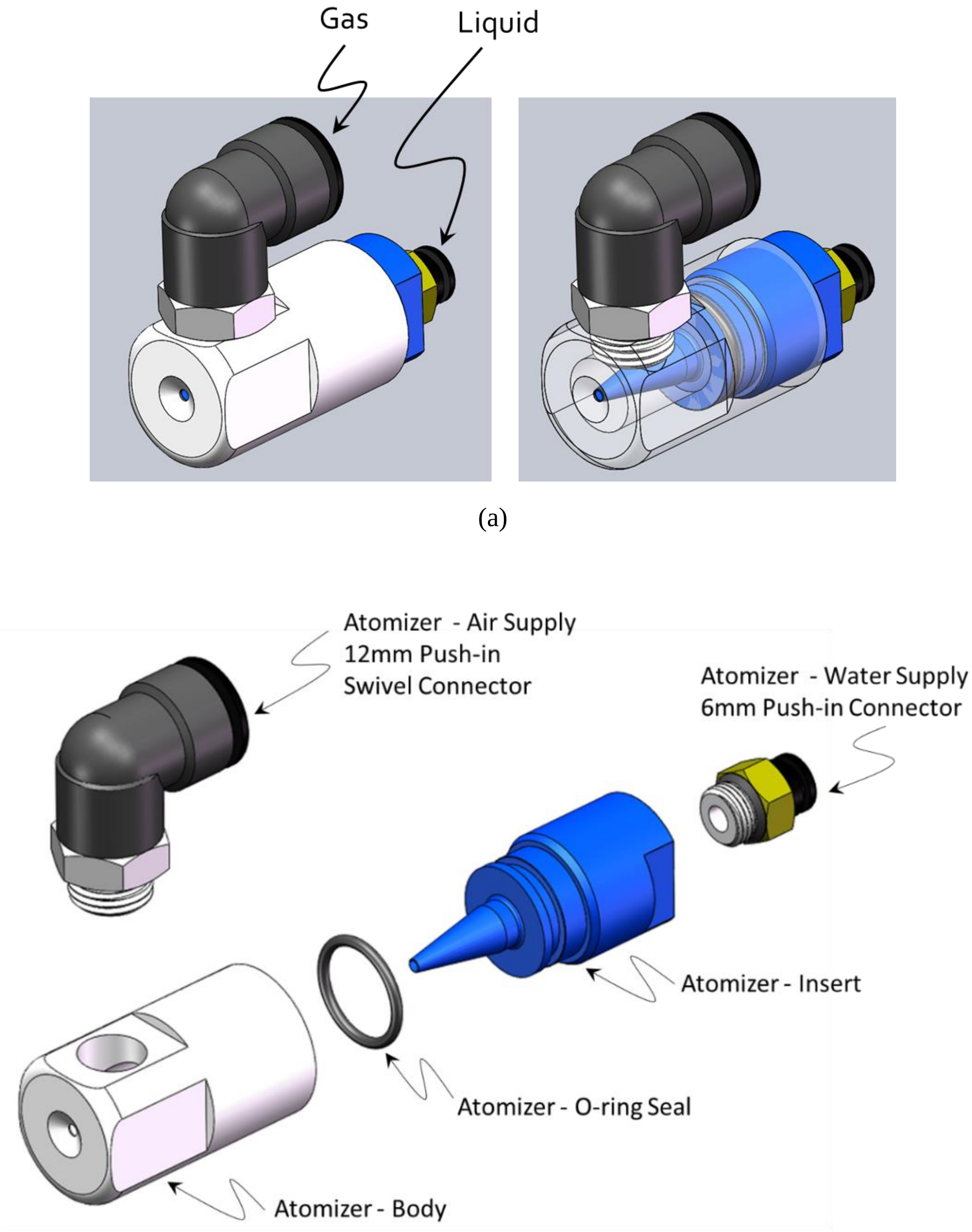
Table 7. FB® atomizer design inputs and outputs parameters

Gas Properties (SI Units): Air		**Liquid Properties (SI Units): Water**		**δ Constants**	
Adiabatic constant γ (air)	1.4	Surface Tension (N/m)	0.073	C_1	0.42
Gas Constant R_g (J/kg*K) (air)	286	Density (kg/m^3)	1000	C_2	18
Ambient Pressure (Pa)	101325	Viscosity (Pa*s)	0.001	C_3	1
Temperature of gas feed (K)	295				
Pressure at Discharge (Pa)	101325				

Table 8. Estimated droplet size results

Case No.	***D* (m)**	***H* (μm)**	**Q_l (ml/min)**	**Q_g (l/min)**	***GLR* (m_g/m_l)**	**Oh_D**	**$dP_{adiabatic}$ (Pa)**	**ρ_g (kg/m^3)**	***U* (m/s)**	**We_D**	**δ**	***MMD* or d_{50} (μm)**
1	0.002	180	63.1	40	0.760	0.0026	258270.2	3.061	589.5	14570.5	0.0038	7.65
2	0.002	180	63.1	38	0.722	0.0026	237389.7	2.814	559.9	12086.8	0.0044	8.87
3	0.002	180	63.1	36	0.684	0.0026	216691.7	2.568	530.5	9902.1	0.0052	10.38
4	0.002	180	63.1	35	0.665	0.0026	206413.7	2.447	515.8	8915.7	0.0056	11.28
5	**0.002**	**180**	**63.1**	**34**	**0.646**	**0.0026**	**196184.5**	**2.325**	**501.0**	**7996.58**	**0.0061**	**12.30**

Figure 13 shows an isometric and exploded views of the atomizer designed under the parameters of case number five (5) and the atomizer specifications.



(a)

(b)

Figure 13. (a) Isometric and (b) exploded view of FB® atomizer

The 2mm atomizer was designed using five main components:

a. Atomizer Body – this component manufactured from stainless steel series (304SS or 316SS), to prevent corrosion in the high humidity environment of the poultry house. The body contains a 2 mm orifice, external flats for torque wrench positioning, 1/4" NPT thread port to accept the 12 mm push-to-connect air connector. Internally it contains a step feature (see Appendix A), to control the "*H*" dimension and 7/8"-14 UNF internal threads to permit the assembly of the atomizer insert, into the atomizer body.

b. Atomizer O-ring seal. – The seal, made out Buna-N material, designed for a static seal size 2-016 and based on specification ASTM D2000/SAE J200. The material selected is well suited for operation in water with temperatures up to 250 ^{o}F

c. Atomizer Insert – this component manufactured from stainless steel 300 series (304SS or 316SS), to prevent corrosion in the high humidity environment of the poultry house. The insert contains a 2mm water conduit, external flats for torque wrench positioning, 7/8"-14 UNF external threads to permit the threading the atomizer insert into the atomizer body. A 1/8" NPT thread port to accept the push-to-connect water connector. Externally, it contains a dimensioned feature (see Appendix A), to control the "*H*" dimension and a gland to accept the O-ring.

d. Atomizer Air Supply Connector – this connector was selected to accept a 12 mm outside diameter (OD) x 10 mm inside diameter (ID) hose. The ID of the hose was sized to handle a flow of 340 LPM and maintain a Mach number (Ma) under 0.2. This design constrain allows the flow distribution analysis to remain in the incompressible flow regime. In addition, the connector provides a "push to-connect" feature that allows the assembly of the atomizer into an air distribution network without tools.

e. Atomizer Water Supply Connector - this connector was selected to accept a 6 mm outside diameter (OD) x 4 mm inside diameter (ID) hose. The connector also provides a “push to-connect” feature that allows the assembly of the atomizer into an air distribution network without tools.

It is important to realize that the parameters in Table 8 (e.g. case 5) are nominal dimensions used in the design process; however, the design must consider manufacturing tolerances. As stated in the droplet size calculation section, the “*H*” dimension is a key characteristic of the FB® atomizer design. In addition, the “*H*” dimension controls the gas flow effective port area (EPA). For these reasons, the manufacturing drawings specify “basic” dimensions callouts for dimensions controlling the “*H*” dimension. Appendix A shows detailed manufacturing drawings for the FB® body and the FB® insert. The “basic” dimensions are enclosed by a rectangle per ANSY Y14.5, while the other dimensions are allowed to fluctuate within a specified tolerance.

The water flow control was achieved with the use of a water dripper. This device, used in the agricultural field for irrigation purposes, controls the water flow to 3.85 LPH (approximately 1 GPH) for inlet pressures between 70 and 350 kPa. The manufacturer of the dripper is Rivulis in Gvat, Israel, and the model number is Supertif Black 3.85 ND. Figure 14 reflects the atomizer assembly as it was installed in the main atomizer sub-assembly of the FB® evaporative cooling system. Push to connect tees of 6mm and 12 mm were added to the assembly to allow the assembly of the atomizer in a parallel configuration.

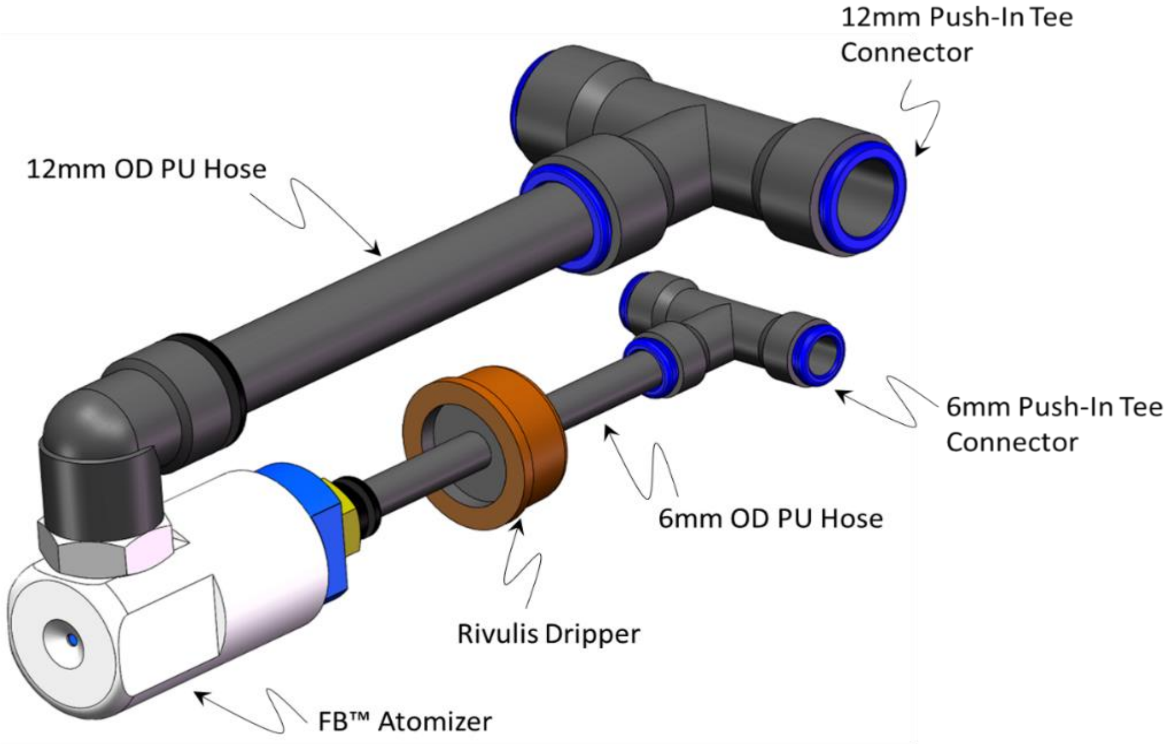


Figure 14. Isometric view FB® atomizer assembly

Following the manufacturing of the atomizer components and assembly, the atomizer assembly went through a validation process. The airflow across the FB® atomizer EPA was measured and results are shown in Table 9. No water was utilized in this testing protocol, to mimic an actual manufacturing environment. This step eliminates the water removal process, increasing the number of atomizers manufactured per hour. The results indicated a discrepancy between the theoretical airflow of 34 LPM and the actual atomizer airflow. This occurrence can be explained by a lower than expected "*H*" value.

Table 9. FB® atomizer airflow at 206.8 kPa (30 psig)

FB® Atomizer No.	Airflow (LPM)
1	20
2	19
3	19
4	19
5	17
6	24
7	23
8	21
9	20
10	24
11	20
12	21
13	23
14	15
15	20
16	23
17	21
18	23
19	19
20	20

It is important to understand the effect the *H* dimension manufacturing tolerances has on the droplet distribution for the FB® atomizer. Atomizers 10, 12 and 14 (highest, average and lowest flows respectively) as illustrated in Table 10, were tested using a SYMPATEC Laser Diffraction Analyzer Model HELOS/BR, Sympatec GmbH, Germany. The pressure was varied from the nominal design pressure of 206.8 kPa (30psi) to 137.8 kPa (20 psi) to simulate a pressure reduction due to wear in the air delivery sub-system. Table 10 and Figure 15 show a summary of the results with the corresponding tests conditions. Figure 16, Figure 17 and Figure 18 show the droplet distribution for atomizer No. 10 at three different operating pressures, where d_{50} diameters of 13.77, 11.53 and 10.04 micro-meters can be identified respectively.

Table 10. H dimension evaluation results

Test No.	Atomizer[1] No.	Relative "*H*" Dimension	Water Flow (LPH)	Gas Pressure (kPa)	Droplet Size d_{50} (µm)	Droplet Size[2] SMD (µm)
1	10	Large	3.85	137.9	13.77	6.95
2	12	Average	3.85	137.9	16.04	8.12
3	14	Small	3.85	137.9	19.26	9.75
4	10	Large	3.85	172.3	11.53	5.97
5	12	Average	3.85	172.3	13.49	6.96
6	14	Small	3.85	172.3	15.30	7.91
7	10	Large	3.85	206.8	10.04	5.38
8	12	Average	3.85	206.8	11.64	6.16
9	14	Small	3.85	206.8	13.00	6.89

Notes: a. 10: Higher flow, larger H, 12: Average flow, average H, 14: Lower flow, smaller H
b. Sauter-Mean Diameter is listed for reference only.

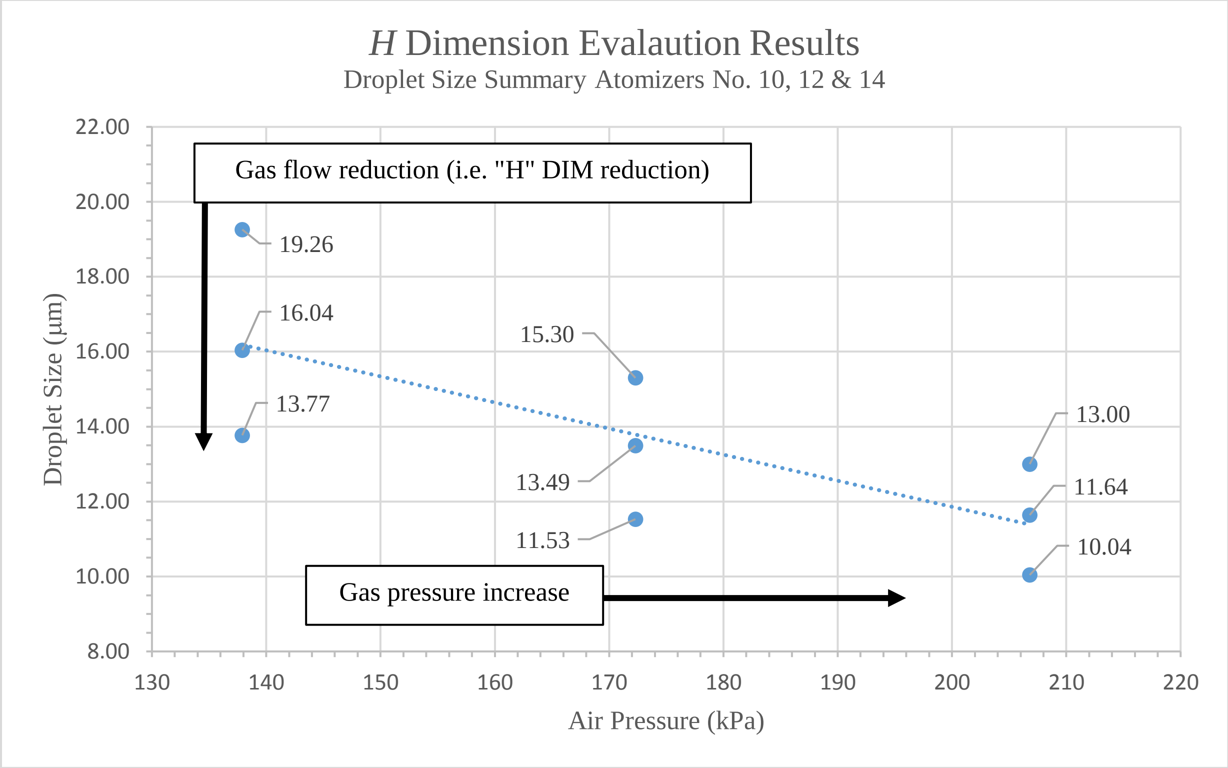


Figure 15. Droplet size distribution summary for FB® atomizers 10, 12 and 14

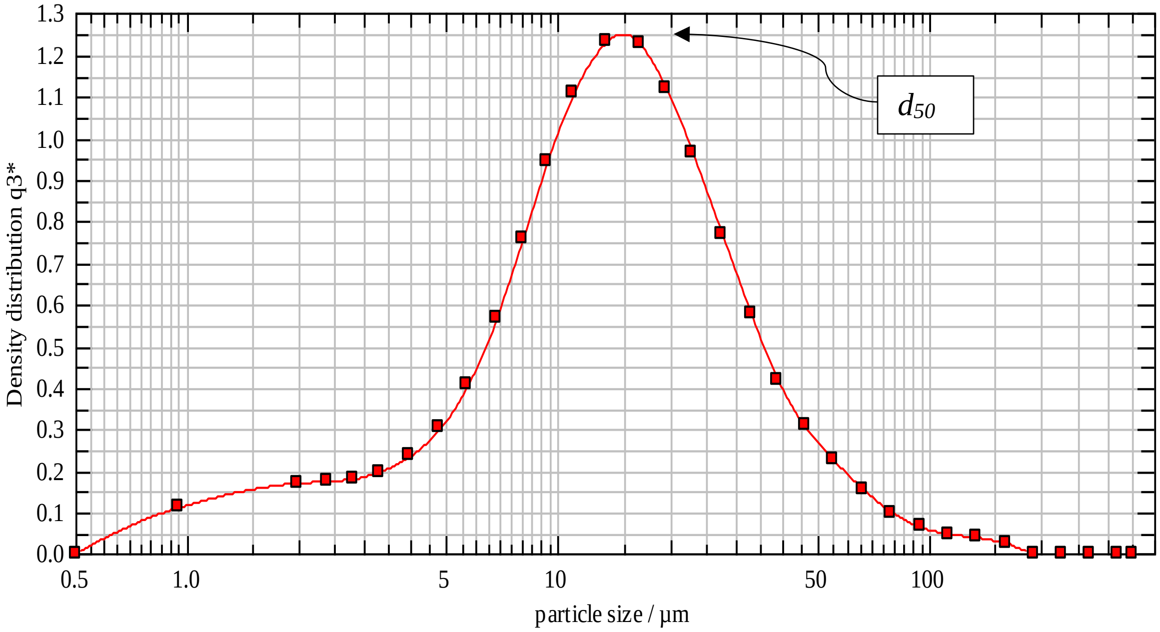


Figure 16. Droplet distribution for FB® atomizer no. 10 at Q_l = 3.85 LPH, P_g = 137.9 kPa. d_{50} = 13.77 µm, SMD = 6.95 µm

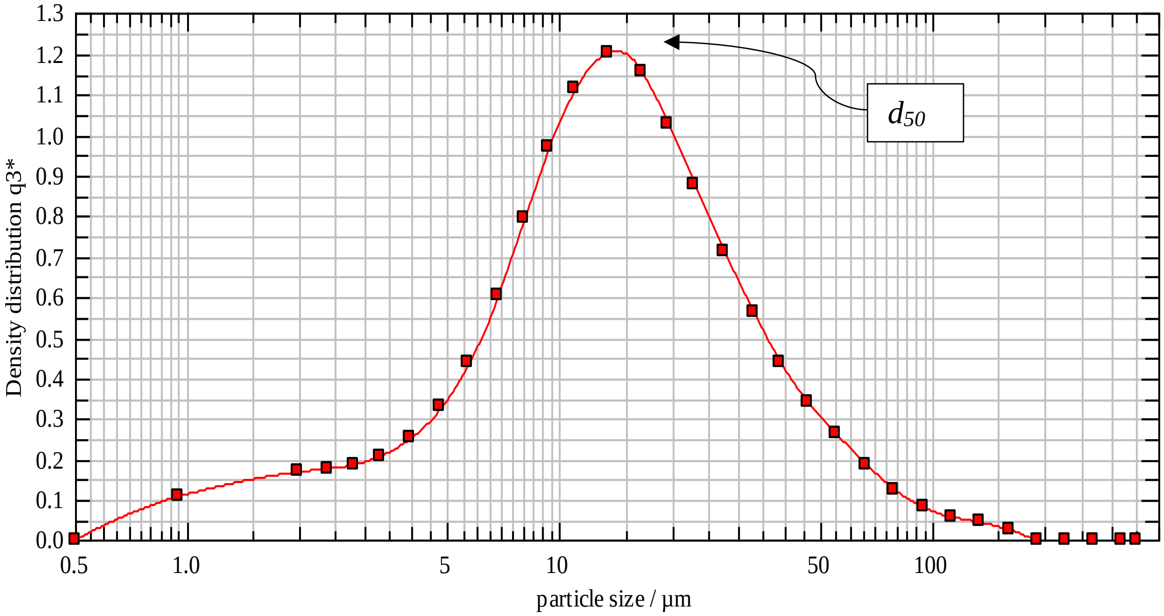


Figure 17. Droplet distribution for FB® atomizer no. 10 at Q_l = 3.85 LPH, P_g = 172.3 kPa. d_{50} = 11.53 µm, SMD = 5.97 µm

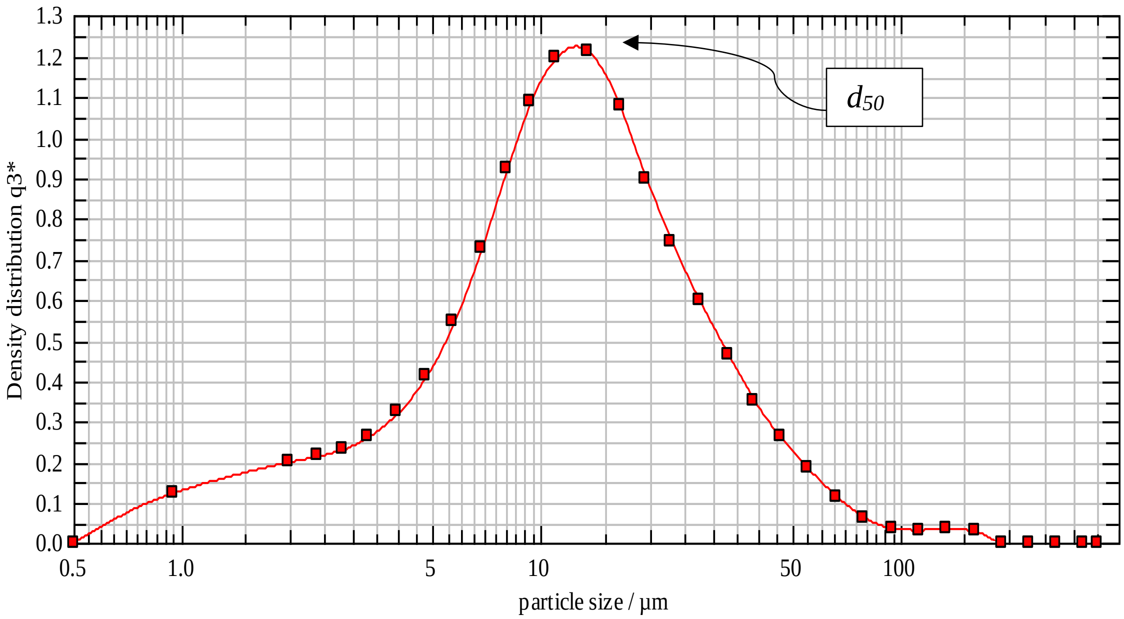


Figure 18. Droplet distribution for FB® atomizer no. 10 at Q_l = 3.85 LPH, P_g = 206.8 kPa**.** d_{50} = 10.04 µm, SMD = 5.38 µm

One can observe from Table 10 that for a constant *H* dimension, test cases 1, 4 and 7 illustrate that an increase in pressure produces a decrease in the droplet size (d_{50} or SMD). This behavior can be explained by an increase in the backflow mixing region as illustrated in Figure 12. This increase in the mixing region produces a larger number of smaller liquid ligaments that forms a larger number of droplet generation sites. Additionally, when the *H/D* ratio is between 0.25 (FB® regime) and a *critical H/D*, the gas to liquid mixing region is reduced, due to a reduction in the EPA (effective port area). This reduces the flow into the mixing region.

3.3. Air and Water Distribution Sub-systems

The operation of the FB® atomizer requires a supply of air and water in a controlled manner. For this reason, it was necessary to develop an air distribution sub-system (ADSS) and a water distribution sub-system (WDSS) to supply the required fluids to each atomizer. The system design had one major constraint. Both poultry houses had a maximum installed amperage of 60A. This limited the available capacity for the installation of the proposed FB®

cooling system, in particular the compressed air equipment. The initial concept of the ADSS had one large compressor, however this created a concern, since a failure of this component could generate a catastrophic incident in the poultry growth cycle. This concern was considered, and the final modular concept was implemented. The modular design consisted of two separated FB® cooling systems with independent compressors (only two modules were used, due the amperage limitation stated before). To ensure the poultry would not be in danger, the current cool-cell system was kept in place, as a backup-system. This measure was requested by the poultry facility, since the facility is an actual poultry process plant, not use for research only. The WDSS was not limited by the available amperage, since it utilized the existing water-well pump pressure. Each module contains one compressor, one pressure regulator, twenty 2mm FB® atomizer assemblies, polyurethane hoses, push to connect fittings, solenoid valves, pressure sensors, and mounting hardware. Table 11provides the supplier and model number for the equipment.

The compressor was selected based on case number 5 (Table 8), which requires 34 LPM/atomizer (1.2 CFM/atomizer) for a total flow of 680 LPM (24 CFM) at a minimum pressure of 206.8 kPa (30 psig). To achieve the water flow control through the atomizer, an agricultural dripper with a capacity of 3.85 LPH (approximately 1 GPH) was used. This dripper provides a cost effective manner to control the flow to the atomizer, between a pressure ranges of 0.7 bar to 3.5 bar (10.2 psig to 50.8 psig). The FB® cooling module (FBCM) concept is illustrated in Figure 19. The automatic FBCM operation logic opens the air solenoid valve first. This step establishes the air in the system, and clears any debris at the FB® atomizer discharge outlet. The water valve shall open, approximately 30 seconds after the air solenoid is open. The system continuously run until the desired temperature is attained or system reaches the maximum limit of relative humidity. These conditions (i.e. temperature and relative humidity) were set per Table 6 in Section 3.1.2, with the exception that the relative humidity upper limit was increased to 70%. This is an increase of only 5% above the limit used at the farm, and allows the FBCM to work longer under this self-imposed constraint. Although it is higher, Yahav [14] has published improvements in weight and feed conversion in Turkeys at this higher humidity level. Upon reaching the desired temperature and/or humidity levels, the system shutdown sequence closes, the water solenoid valve first, stopping the flow of water to the atomizers. Then, the air solenoid valve remain open for an additional minute. This extra air flow ensures that moisture is eliminated at the FB® atomizer outlet. This is beneficial, in case the source of water contains a high concentration of minerals (i.e. hard water). These minerals can be deposited with time, after standing water evaporates and cause a risk for the atomizer to clog.

Table 11. FB® cooling system equipment per module

Item No.	Description	Supplier	Part Number	Quantity
1	Compressor	Jenny Compressors	J5S-80V	1
2	2mm FB® Atomizer (Note 4)	Note 1	Note 1	20
3	Air Pressure Regulator	McMaster-Carr	4959K203	1
4	Humidity/Temperature Transmitter	Dwyer	RHP-202B	3
5	Brass Solenoid Valve, Buna-N Diaphragm, Normally Closed, 1/2 NPT Female, 24V AC	McMaster-Carr	4711K733	2

Table 11 (Continued)

6	12mm OD High-Pressure Nylon Tubing Opaque, 10 mm ID, 12 mm OD Hose	McMaster-Carr	5140K825	Note 2
7	High-Pressure Nylon Tubing, Opaque, 4 mm ID, 6 mm OD	McMaster-Carr	5140K234	Note 2
8	Pressure Transducer	McMaster-Carr	3196K5	1
9	Controller	DISTECH Controls	EC-BOS-6	1[3]
10	Dripper	Rivulis	Supertif Black 3.85 ND	20

Notes:

1. This part was custom designed and manufactured for this project. Refer to Figure 14 for components in the assembly
2. This quantity is estimated to be 38.1 m (125 ft)
3. The controller was shared by the two installed cooling modules
4. Designed per Table 8, case 5

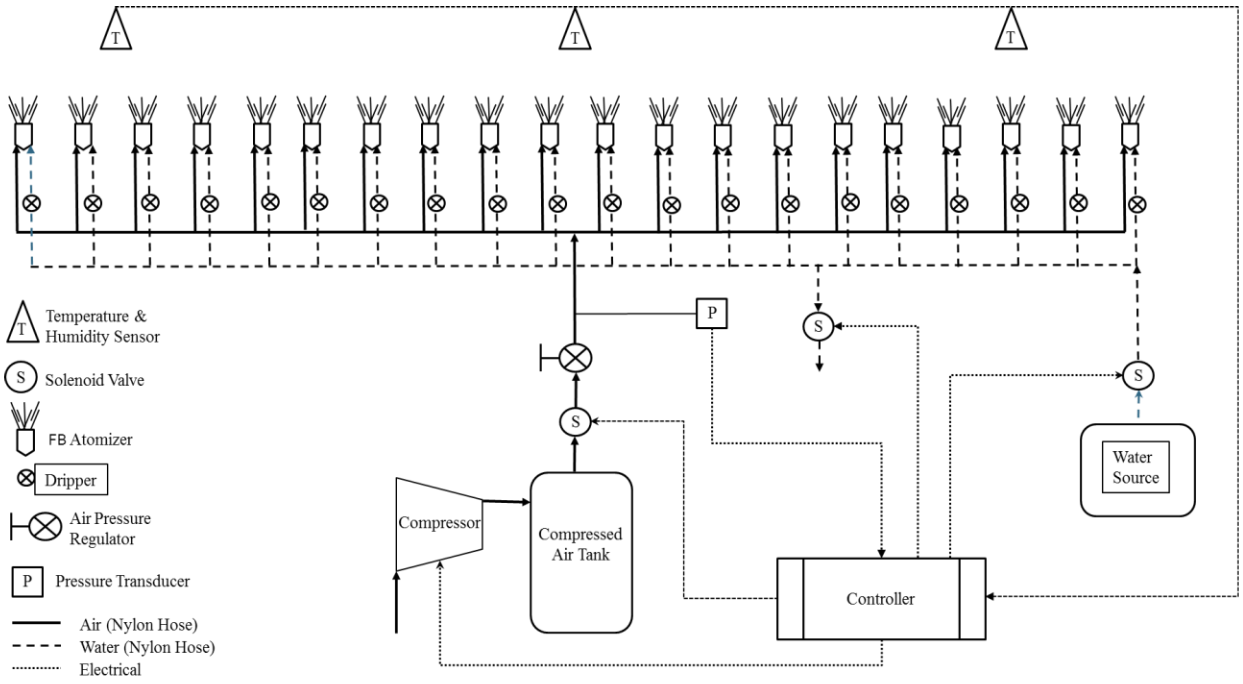


Figure 19. FB® cooling module schematic

Analysis of the theoretical model illustrated in Figure 19 was performed using PIPEFLOW Expert V7.3, to estimate the pressure drop of the conceptual system, and ensure the proposed air compressor had enough capacity (i.e. flow and power). This commercially-available software uses a compressible gas flow with general fundamental isothermal flow equation and Colebrook-White friction factor [50],

$$w = 316.23\sqrt{\frac{A^2}{v_1\left(\frac{fL}{D} + 2\ln\frac{p_1}{p_2}\right)}\left(\frac{p_1^2 - p_2^2}{p_1}\right)} \tag{12}$$

where, w is the mass flow rate, in kilograms per second, A is the cross sectional area of pipe or orifice, in square meters, v_1 is the specific volume of fluid, in cubic meters per kilogram ($at\ p_1$), f is the friction factor, L is length of pipe, in meters, D is the internal diameter of pipe, in meters and p is the pressure, in bar absolute. The equation has been developed under the following assumptions,

- Isothermal flow
- No mechanical work done on or by the system
- Steady state flow
- Air behaves as an ideal gas (i.e. Z= 1)
- The velocity of the gas may be represented by the average velocity at a conduit cross section
- The friction factor is constant along the pipes
- The pipes are straight and horizontal between end points

Figure 20 shows the FBCM concept and PIPEFLOW model. A solution was obtained, after several iterations where the pressure regulator was adjusted and the system met the required parameters.

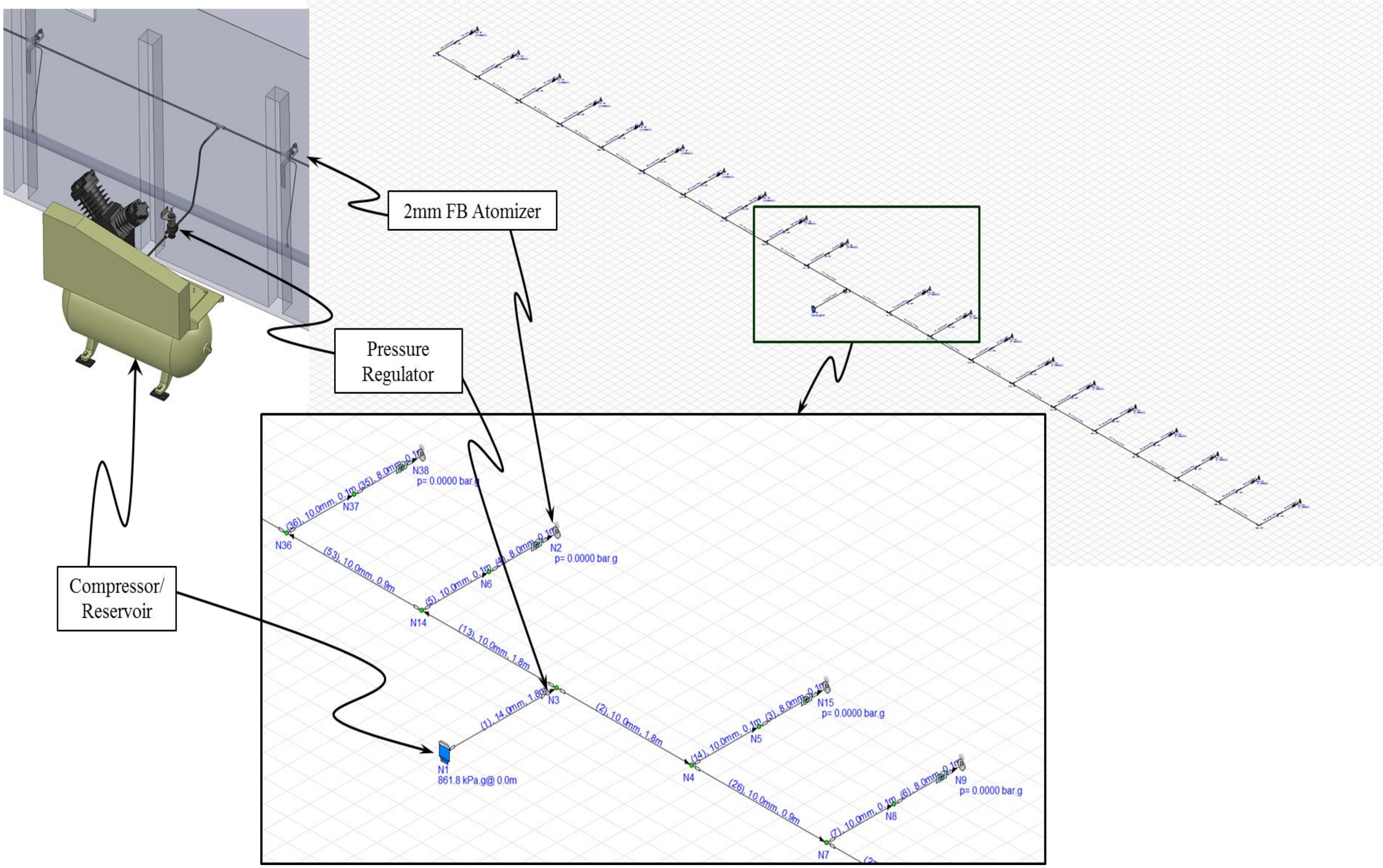


Figure 20. PIPEFLOW model design of FB® cooling module

Table 12. PIPEFLOW air distribution results

Pipe No.	Inner Diameter (mm)	Length (m)	Gas Flow (LPM)	Exit Mach#	Entry Pressure (bar.g)	Exit Pressure (bar.g)
1	14	1.83	685.8	0.07	8.62	2.24
2	10	1.83	342.9	0.07	2.24	2.18
3	8	0.05	35.5	0.03	2.18	0.00
4	8	0.05	35.5	0.03	2.18	0.00
5	10	0.05	35.4	0.01	2.18	2.18
6	8	0.05	35.2	0.03	2.15	0.00
7	10	0.05	35.0	0.01	2.15	2.15
8	8	0.05	35.0	0.03	2.12	0.00
9	10	0.05	34.8	0.01	2.12	2.12
10	8	0.05	34.8	0.03	2.11	0.00
11	10	0.05	34.6	0.01	2.11	2.11
12	8	0.05	34.7	0.03	2.09	0.00
13	10	1.83	342.9	0.07	2.24	2.18
14	10	0.05	35.4	0.01	2.18	2.18
15	10	0.05	34.4	0.01	2.09	2.09
16	8	0.05	34.6	0.03	2.08	0.00
17	10	0.05	34.3	0.01	2.08	2.08
18	8	0.05	34.5	0.03	2.08	0.00
19	10	0.05	34.3	0.01	2.08	2.08
20	8	0.05	34.5	0.03	2.07	0.00
21	10	0.05	34.2	0.01	2.07	2.07
22	8	0.05	34.5	0.03	2.07	0.00
23	10	0.05	34.2	0.01	2.07	2.07
24	8	0.05	34.5	0.03	2.07	0.00
25	10	0.05	34.0	0.01	2.07	2.07
26	10	0.91	307.6	0.06	2.18	2.15
27	10	0.91	272.7	0.06	2.15	2.12
28	10	0.91	238.1	0.05	2.12	2.11
29	10	0.91	203.7	0.04	2.11	2.09
30	10	0.91	169.4	0.03	2.09	2.08
31	10	0.91	135.3	0.03	2.08	2.08
32	10	0.91	101.3	0.02	2.08	2.07
33	10	0.91	67.4	0.01	2.07	2.07
34	10	0.91	33.6	0.01	2.07	2.07
35	8	0.05	35.2	0.03	2.15	0.00
36	10	0.05	35.0	0.01	2.15	2.15
37	8	0.05	35.0	0.03	2.12	0.00
38	10	0.05	34.8	0.01	2.13	2.12
39	10	0.05	34.6	0.01	2.11	2.11
40	8	0.05	34.8	0.03	2.11	0.00
41	8	0.05	34.7	0.03	2.09	0.00
42	10	0.05	34.4	0.01	2.09	2.09
43	8	0.05	34.6	0.03	2.09	0.00
44	10	0.05	34.3	0.01	2.09	2.09
45	8	0.05	34.5	0.03	2.08	0.00
46	10	0.05	34.3	0.01	2.08	2.08
47	8	0.05	34.5	0.03	2.08	0.00
48	10	0.05	34.2	0.01	2.08	2.08
49	8	0.05	34.5	0.03	2.07	0.00
50	10	0.05	34.2	0.01	2.07	2.07
51	8	0.05	34.5	0.03	2.07	0.00
52	10	0.05	34.0	0.01	2.07	2.07
53	10	0.91	307.6	0.06	2.18	2.15
54	10	0.91	272.7	0.06	2.15	2.13
55	10	0.91	238.1	0.05	2.13	2.11
56	10	0.91	203.7	0.04	2.11	2.09
57	10	0.91	169.4	0.03	2.09	2.09
58	10	0.91	135.3	0.03	2.09	2.08
59	10	0.91	101.3	0.02	2.08	2.08
60	10	0.91	67.4	0.01	2.08	2.07
61	10	0.91	33.6	0.01	2.07	2.07

Table shows the results of the PIPEFLOW analysis. It is important to highlight the pipes number 24 and 51, which are the last pipes on the right and left side respectively. The required flow of 34 LPM at 196.2 kPa was met. Table 13 illustrates a summary of requirement vs. estimated delivery based on analysis.

Table 13. Required atomizer airflow at pressure vs. estimated air delivery sub-system airflow at pressure

	Pressure (kPa)	Air Flow (LPM)
Required air delivery to the FB® atomizer per Table 7 Case 5	196.2	34
Estimated air delivery of ADSS Design, at the FB® atomizer	206.4	34

The desired air delivery of ADSS design, occurred at a pressure regulator setting of 220.6 kPa (32 psi). This pressure was used as the initial setting for system operation during the testing phase.

The design of the FBCS installed in the poultry is illustrated in Figure 21, with the exception of the compressor. The compressor purchased for the test had a vertical reservoir configuration, rather than the horizontal configuration shown in the design. This change in reservoir configuration had no effect on the FBCS performance. Figure 22 shows the compressor as installed during testing. Two of the proposed FBCS were installed in the poultry house 4 and testing performed during July 17 through August 28, 2015. Test results are presented in Chapter 4.

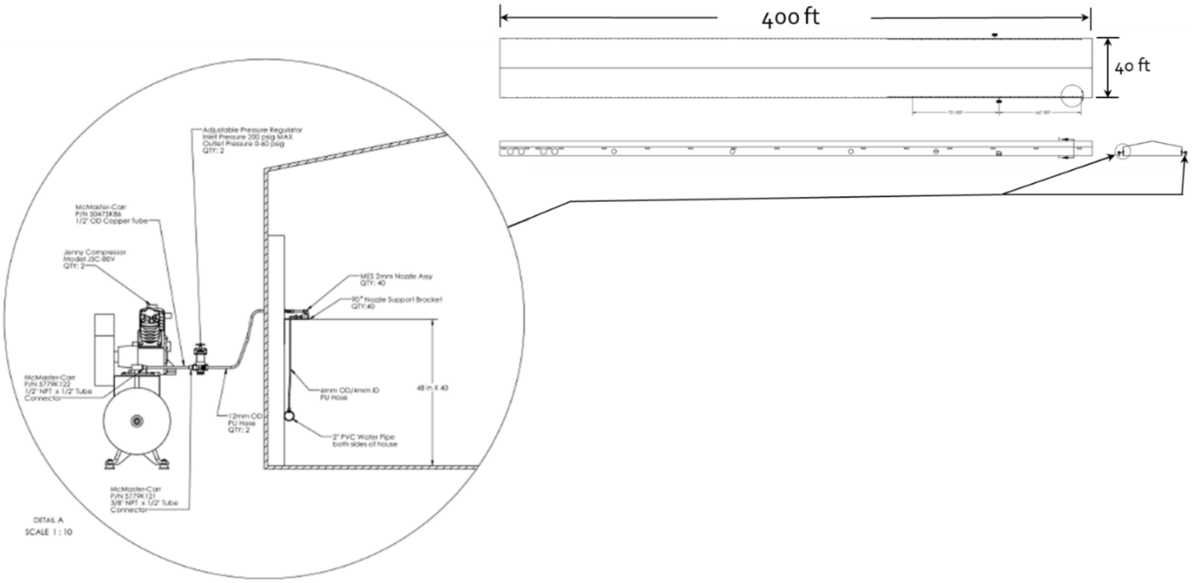


Figure 21. Proposed FBCS design

Figure 22. FBCS compressor with vertical air reservoir configuration as installed at poultry house

Chapter 4: Experimental Results and Discussion

This chapter presents the quantitative results to address the two research questions:

a. Can a Flow Blurring® atomization system achieve the necessary cooling and humidity control in a poultry house, and reduce the water consumption during this process?

b. Can this system facilitates the growth of protein in locations where water is a prime resource?

Research question 1 is very important since, for any system to be viable, cooling and humidity control are required. Systems must be capable of providing the required cooling characteristics for a successful poultry growth cycle. Figure 23 illustrates the measured average dry-bulb temperature through the 42 day growth process. As delineated by the plotted linear trend line, dry-bulb temperature decreases as the growth cycle progresses. This temperature drop is a consequence of the increase in mechanical ventilation that removes heat from the house, in addition to the removal of heat by the evaporative cooling system. The average dry-bulb temperature for house number 4 (house modified with the FB® cooling system), was at or below the house number 3 (house with Cool-Pads) as illustrated in Figure 23. It is essential to note that the dry-bulb temperature of both houses was above the ideal temperature (temperature set point) documented in Table 6 of section 3.1.1. This reflects the importance of air velocity within the house, which created a wind chill factor over the poultry. This effect brings the effective poultry temperature closer to the desired ideal temperature.

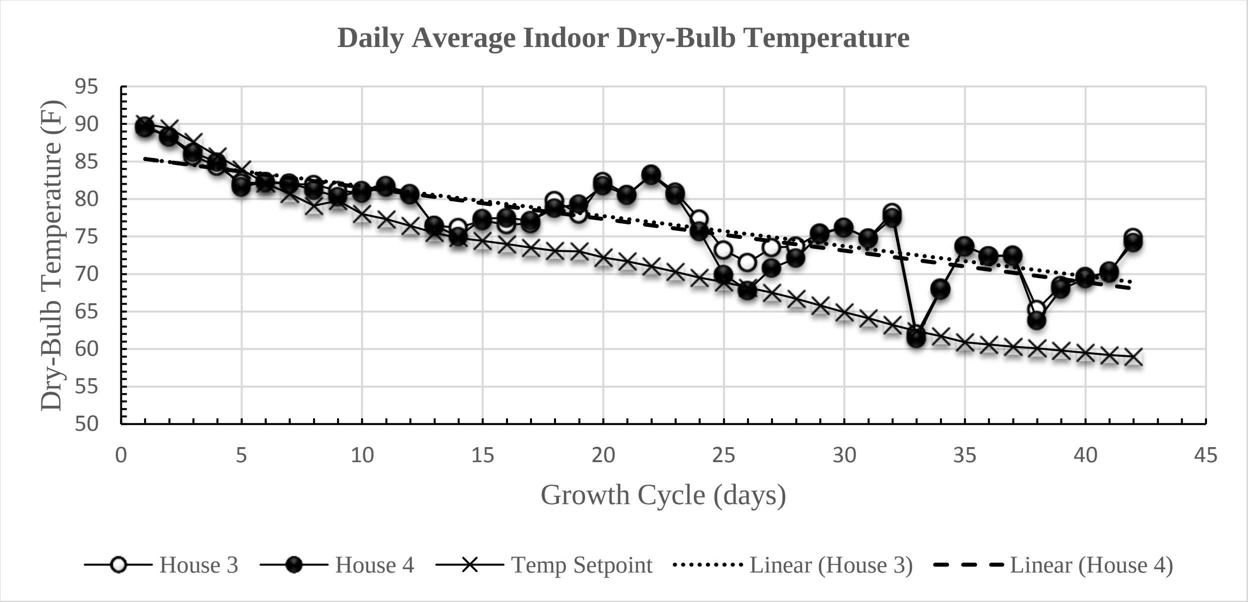


Figure 23. Average dry-bulb temperature of house 3 and house 4

A second key element of research question 1 is the humidity level within the houses. The humidity level of house 4 (H4) was maintained below house 3 (H3) from day 1 to day 33, as illustrated in Figure 24. Inflexion points are evident for both humidity curves at day number 33, where the humidity level reversed in both houses. Inquiry of this specific characteristic, revealed that the farm manager noticed the poultry panting more frequently than normal in his experience. On this day, the manager activated the Cool Pad system in H4. This event may potentially explain the increased humidity in H4.

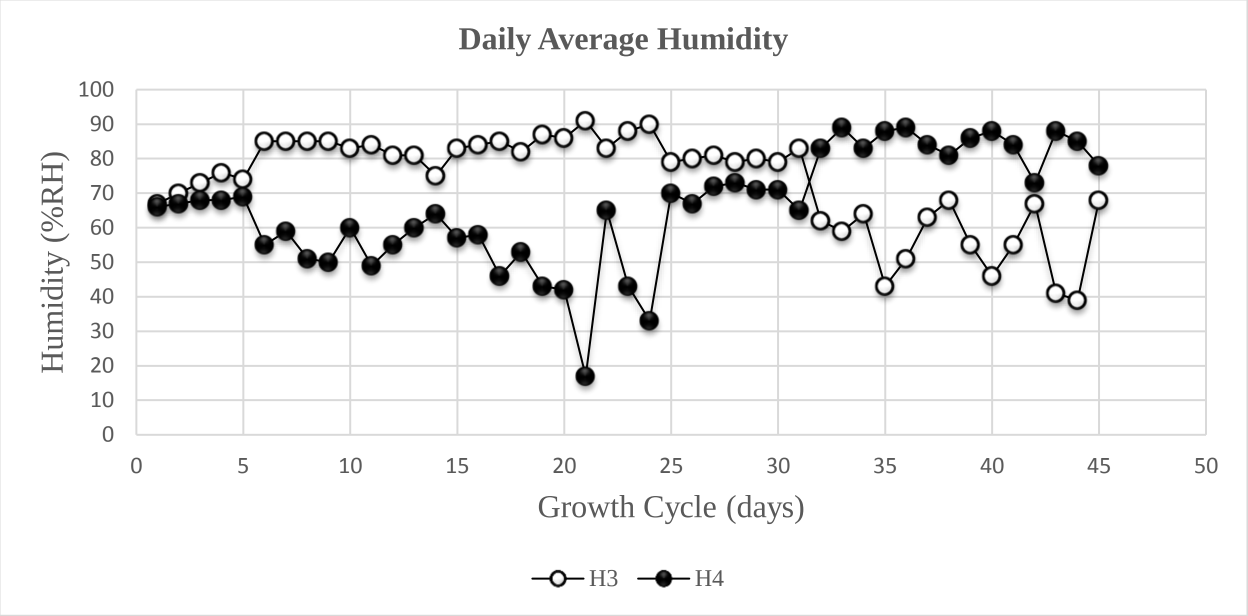


Figure 24. Daily average humidity levels for houses 3 and 4

As part of this study, the humidity of houses 1 (H1) and 2 (H2) as illustrated in Figure 10, was plotted in conjunction with data from H3 and H4. Although these houses were not the main focus of this study, they have the same Cool Pad system as in H3 and H4, and data is always collected for all four houses during the growth cycle. Figure 25 illustrates the humidity for all four houses. Of note, H1, H2 and H4 follows a similar trend. However, the humidity of H3 drops, even though all four houses operate under the same outdoor dry-bulb and wet-bulb conditions. Particularly relevant is the fact that in Figure 23, H3 and H4 have very similar indoor temperature, indicating an evaporative cooling process must be in place. One possible explanation of the sudden drop in humidity maybe a malfunction of the humidity sensor(s) in H3.

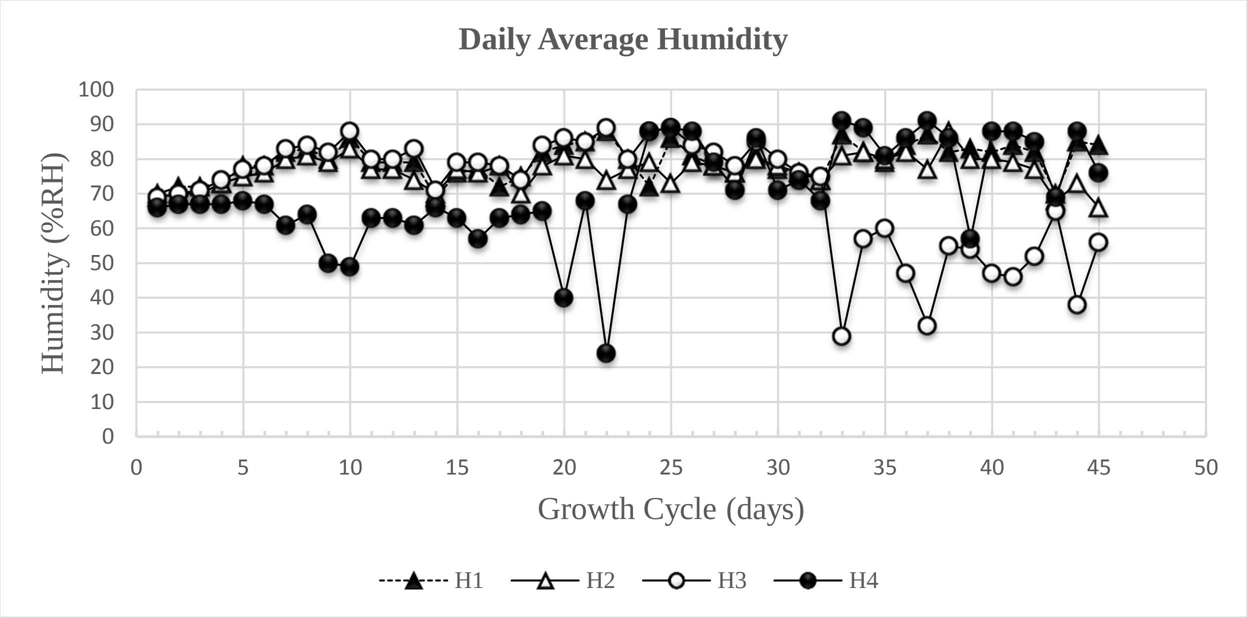


Figure 25. Daily average humidity levels for houses 1, 2, 3 and 4

Figure 26 illustrates the relative humidity for all four houses during the growth cycle period from July 31st to September 10th of 2014. As observed, the relative humidity of all houses follows a similar pattern. The humidity is expected to increase as a function of the growth cycle, by means of biological byproducts and moisture added via the evaporative cooling system. Both humidity sources increases as the poultry increases in weight as part of the cycle. This finding may provide some indication as to the anticipated tendency of the humidity, which counters that of H3.

It is important to note that the FBCS was under-sized from the start of the testing, due to the limited electrical installation (60 amps max.). This may have influenced a premature decision to switch from the FBCS to the Cool Pad system in H4. Although the FBCS was performing well under the imposed conditions, this was still an actual field test (i.e. actual business) and priorities changed instantly to ensure the well-being of the birds.

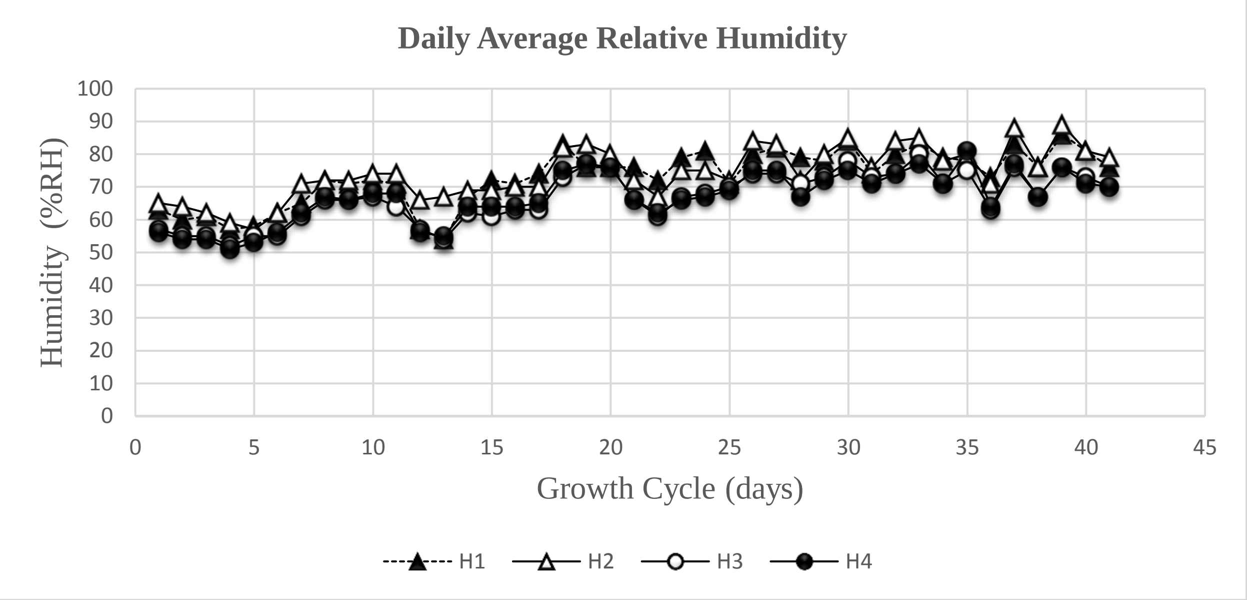


Figure 26. Relative humidity data collected for H1, H2 H3 and H4 between July 31 and September 10, 2014

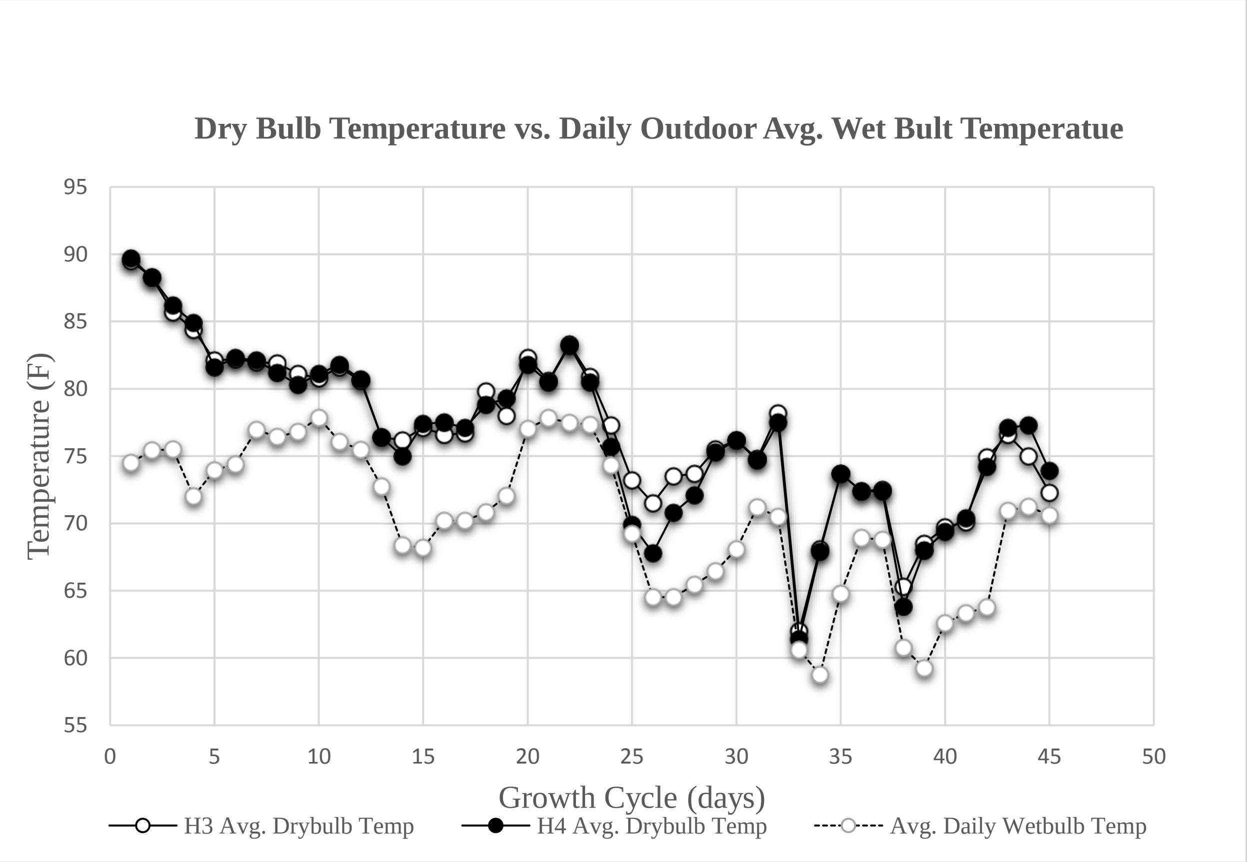


Figure 27. Average daily outdoor wet-bulb temperature and average indoor dry-bulb temperature for houses 3 and 4

The data shown in Figure 27 illustrates the dependency of the evaporative cooling process performance on the outdoor wet-bulb temperature. The indoor dry-bulb temperature tracks with the trends of the outdoor wet-bulb temperature. As stated in Section 2.2, the evaporative cooling proceeds until the dry-bulb temperature matches the outdoor wet-bulb temperature, when the air reaches complete saturation (i.e. 100% relative humidity). Although there is room to drop the temperature even further, this is not desired, since poultry releases a large portion of their body heat through the panting process as described in Section 2.1.2. This is the reason why controlling temperature and humidity is essential to the process.

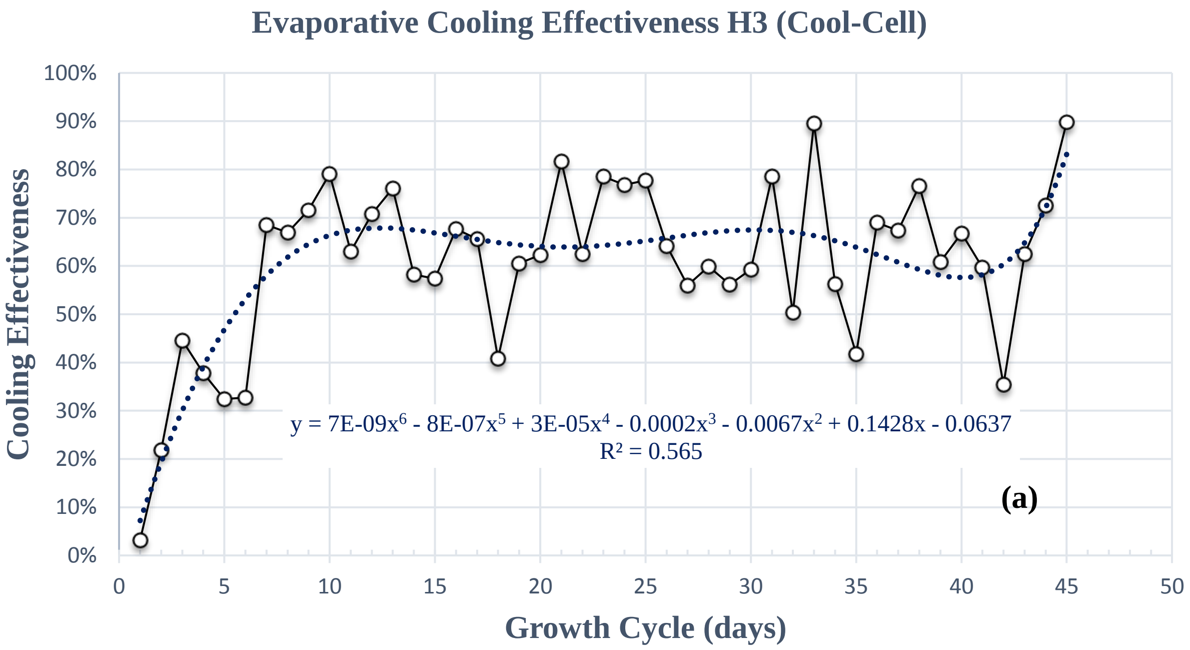
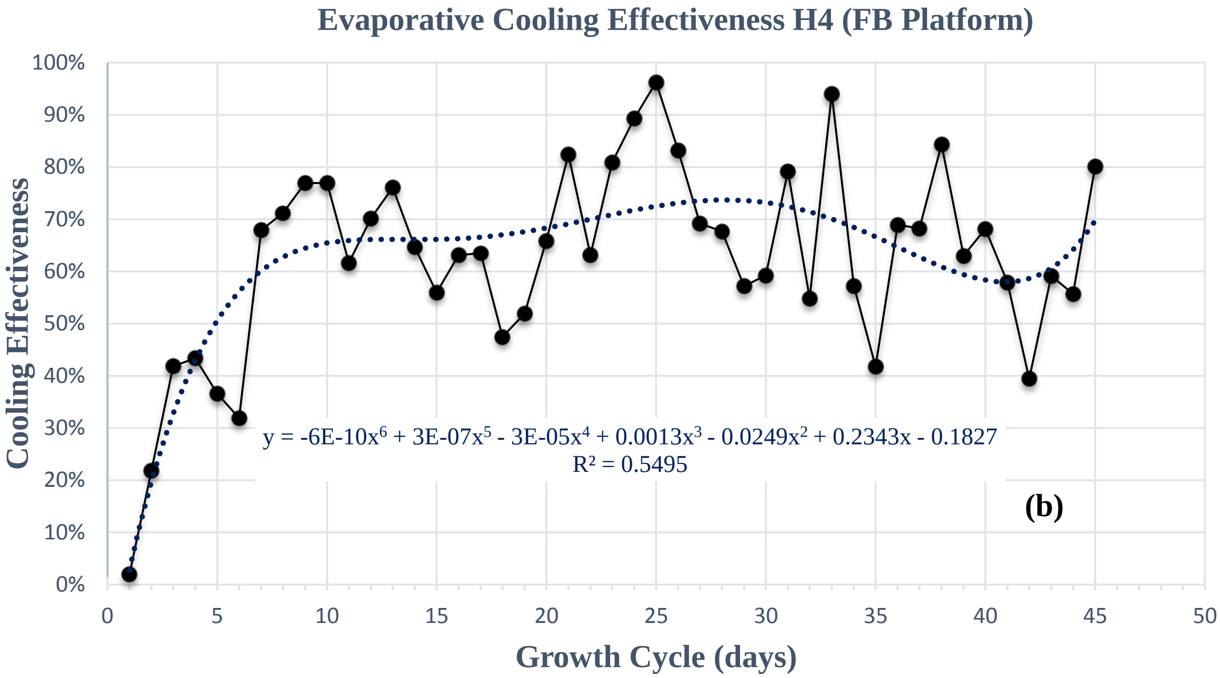


Figure 28. Evaporative cooling effectiveness of (a) H3, (b) H4.



(b)

Figure 28 (Continued)

The evaporative cooling effectiveness described in Section 2.2 is another factor to be used to compare the performance of the existing Cool-Pad and the proposed Flow Blurring® cooling systems. Figures 28(a) and (b) illustrate the cooling effectiveness of H3 and H4 respectively. It is noteworthy that the effectiveness between both systems is comparable between days 1 through 15. This is due to the fact that initially the poultry can be cooled via mechanical ventilation. However, between day 15 and 33, the effectiveness of H4 is higher than H3 by an average of 4.1%. After day 33, the effectiveness of each house is again very similar, due the event where the Cool-Pad system was brought on line as a safety precaution.

Research question number 2, investigated whether this system facilitates the growth of protein in locations where water is a prime resource. As introduced in Chapter 1, protein production is increasing in developing countries throughout the world. This increase results in higher demand for water, the most important natural resource to sustain life. Therefore, any reduction of water consumption, while increasing protein production will be a significant benefit, especially in countries where water is scarce (e.g. Middle East, Africa, and parts of Asia). Figure 29 shows the consumption of water in H3 and H4. A reduction in water consumption of 13,368 gallons was recorded between days 1 to 42, between H3 and H4. Approximately 78% (10443 gallons) of the water usage reduction occurred during days 15 thru 3, when the FBCS was in operation. This is a significant amount of water when considering that in 2012 there were about 233,770 poultry houses in the United States alone [51]. Assuming each farm/cooling system can run between the months of May through September (i.e., 5 months), and the production cycles are approximately every 52 days (42 days production and 10 for preparation between cycles), the system could run for 2.88 cycles annually. This means the U.S system alone can save over 6.7 billion gallon of water per year (2.88 cycles/year*233,770 farms*10,000 gallon/cycle). This amount of water is equivalent to the water required to fill 10,200 Olympic size pools.

Reposing the initial questions, can a Flow Blurring® Cooling System facilitate the growth of protein in locations where water is a prime resource? Based on the facts presented, the answer is yes. Even if water is not scarce, we must consider any measures to reduce this valuable natural resource.

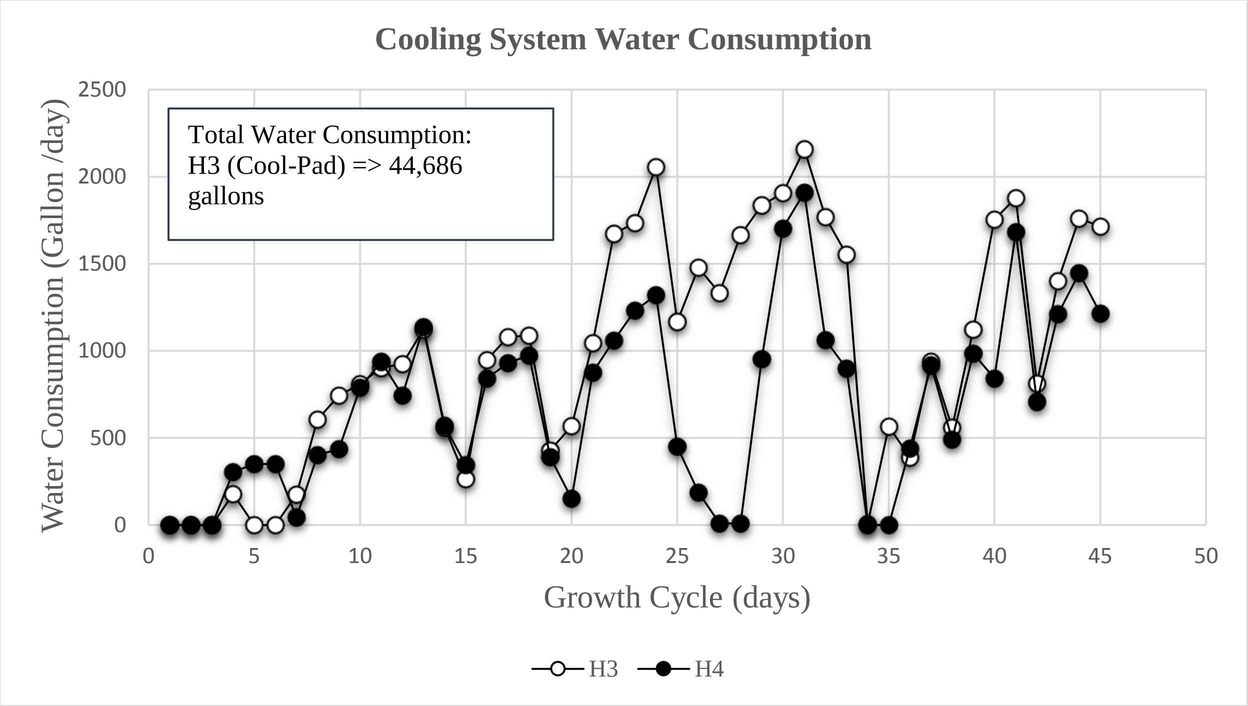


Figure 29. Consumption of water between FBCS and cool-pad systems

Another characteristic of the proposed FBCS is power consumption. This is crucial since the electrical installation for these operations (i.e. poultry houses) is around 60 amps, and limits the amount of retrofit equipment that can be added. Figure 30 illustrates the daily average power consumption of H3 and H4 during the growth cycle. In this instance, power consumption is similar between days 1 through 15 for both houses, but increases for H4 after day 15. This is in conjunction with the required need for compressed air for the FB® atomizers. Although it is evident more power is required for this process, energy can be obtained from many other sources like, Aeolic and/or Solar energy. This presents a real opportunity, given the roof area available for solar panels installation. In most developing countries, lack of water is more critical than power availability, which can be easily acquired from the sun. Therefore, based on the data presented in Chapter 4, it is appropriate to consider the Flow Blurring® cooling system as a viable solution to Research Question 2.

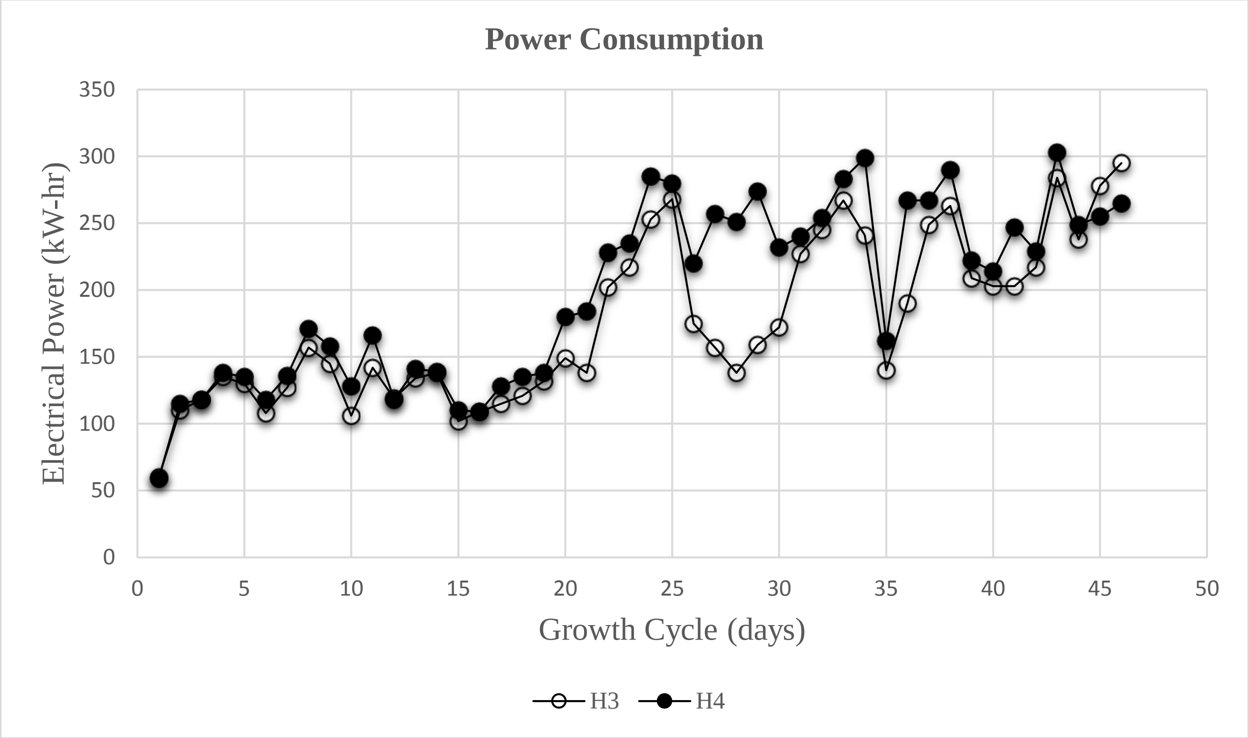


Figure 30. Daily average power consumption of H3 and H4

Chapter 5: Conclusions and Future Work

5.1. Conclusions

In this dissertation, an evaporative Flow Blurring® cooling system (FBCS) was designed, manufactured, installed, and experimentally investigated. The FBCS was designed to match the cooling load required for a poultry house located near Fayetteville, AR., during the summer time (July-August). Specifications were based on the existing building construction, real production occupancy and relevant environmental requirements. One key feature of the system design included the development, manufacturing, and testing of a custom Flow Blurring® atomizer. Additionally, a control system (i.e. controls logic) was developed to run the sequence of actions required during the operation (on/off cycles) of the system. Experimental results of from the FBCS were compared to an existing Cool-Pad evaporative system, the current standard in the poultry industry.

Implementation of this new evaporative cooling system resulted in a reduction of approximately 78% in water consumption (10,443 gallons) used for cooling, while the FBCS and Cool-Pad systems were concurrently in operation The reduction in use of this irreplaceable natural resource occurred while the FBCS maintained comparable and/or enhanced environmental conditions (i.e. temperature and humidity). These results clearly demonstrate the validity for the application of a FBCS in the poultry agricultural field.

A correlation was established between developing countries with population and economic growth, and the increasing demand for animal protein. In addition, poultry meat (e.g. chickens, turkeys, and others) has been identified as having a relatively lower water footprint, when compared to beef or pork. Therefore, the addition of a FBCS to the supply chain of poultry protein can be a significant improvement in geographical regions where water resources are scare, as well as in countries where water is abundant. Life as we know it can exist without oil, but not without water.

5.2. Future Work

Recommended future work, based on the experimental investigation and results obtained in this research include:

a. The experimental setup should use a poultry house with enough electrical capacity to install the full FBCS (four modules). This shall allow the farm manager to operate the system with confidence for the full 42 days growth cycle.

b. Cooling effectiveness should be evaluated vs. atomizers elevation in the house (with respect from the litter). A higher elevation may increase the contact time with the incoming air and in terms the evaporation process.

c. Power consumption can be a concern to the farmer, as it increases the operation's recurrent costs. However, the rural location of these facilities, permits the addition of renewable energy sources (e.g. Aeolic, biodiesel, solar, etc.) that can allow the installation of a poultry house in remote locations where the power infrastructure is limited or not available. A study of the lifecycle water consumption between current vs. renewable energy source may provide a more comprehensive water footprint.

d. The atomization knowledge acquired (in terms of droplet size control) creates the following question: Can we control the droplet size to use the Flow Blurring® cooling system for an indirect evaporative cooling? This would be a significant improvement, since the temperature of the air can be reduced, without an increase in humidity.

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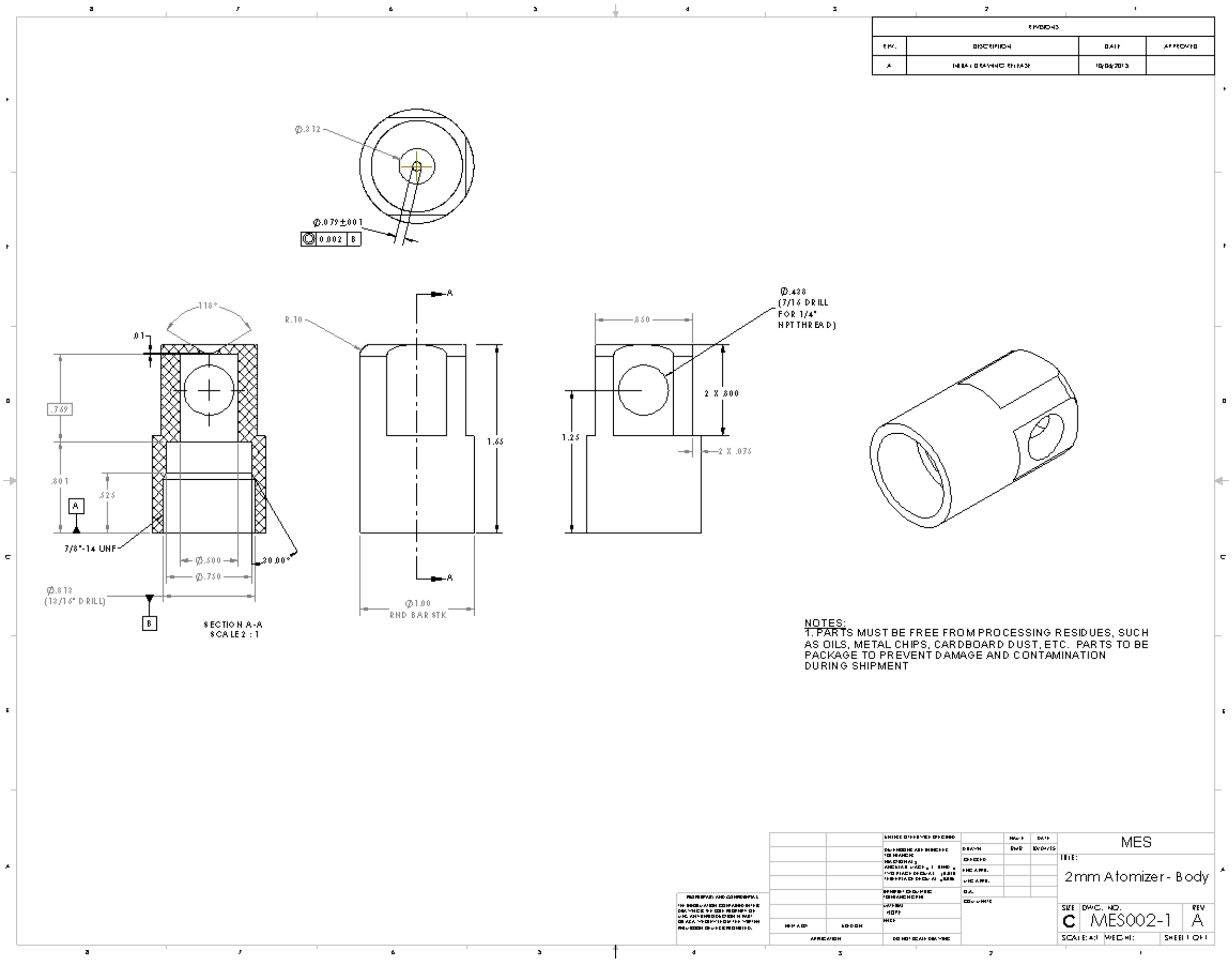
Appendix A: Detailed Drawings



NOTES:
1. PARTS MUST BE FREE FROM PROCESSING RESIDUES, SUCH AS OILS, METAL CHIPS, CARDBOARD DUST, ETC. PARTS TO BE PACKAGE TO PREVENT DAMAGE AND CONTAMINATION DURING SHIPMENT

Figure A. FB® atomizer body 2D detailed drawing

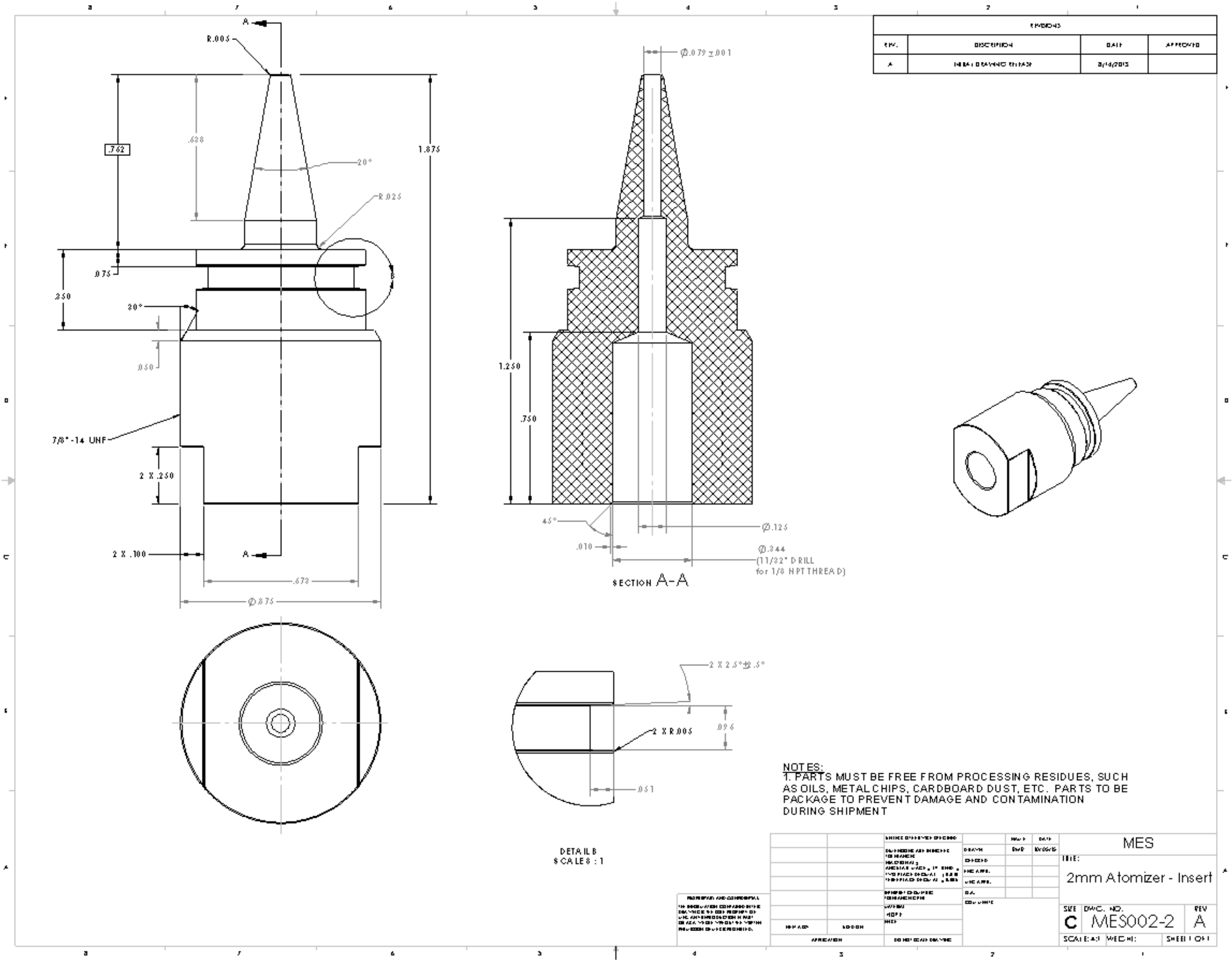


Figure B. FB® atomizer insert 2D detailed drawing

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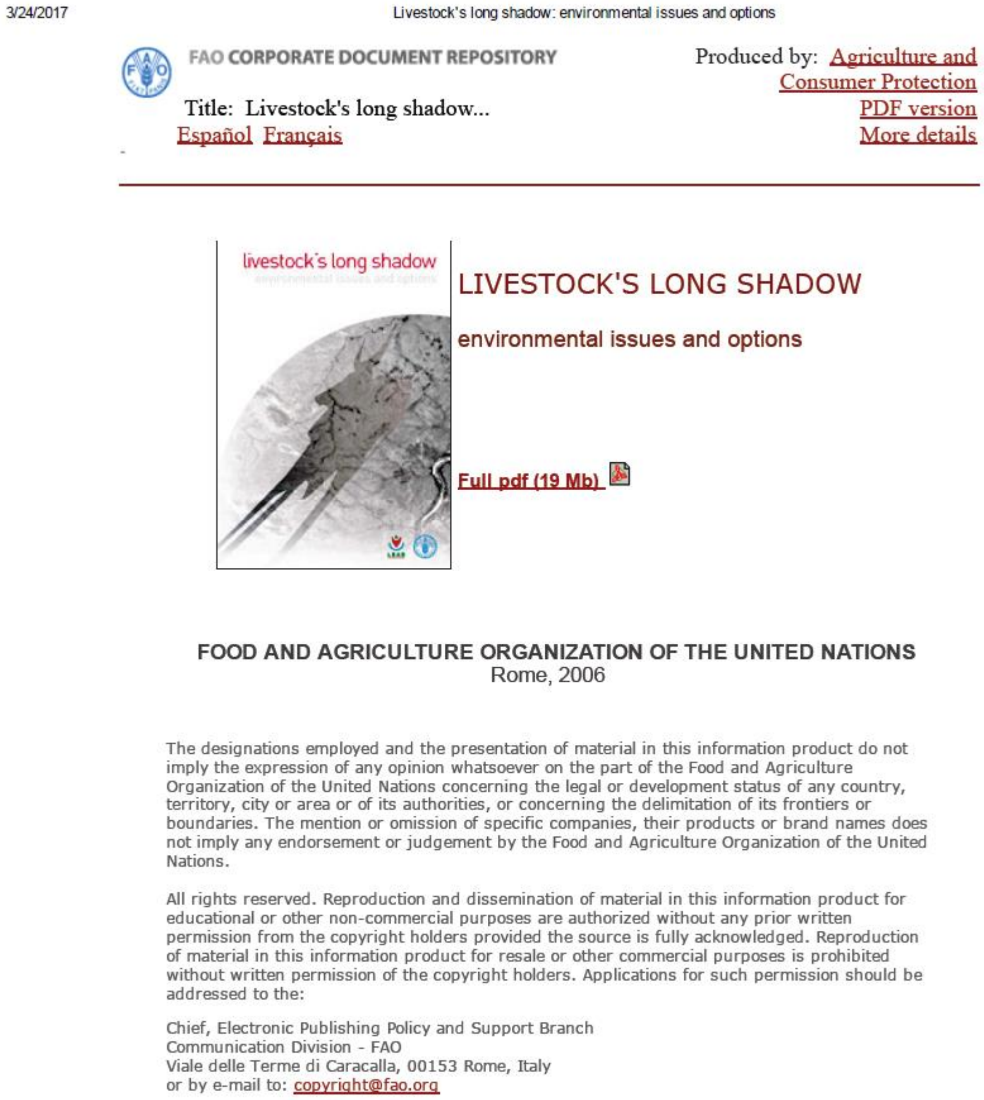

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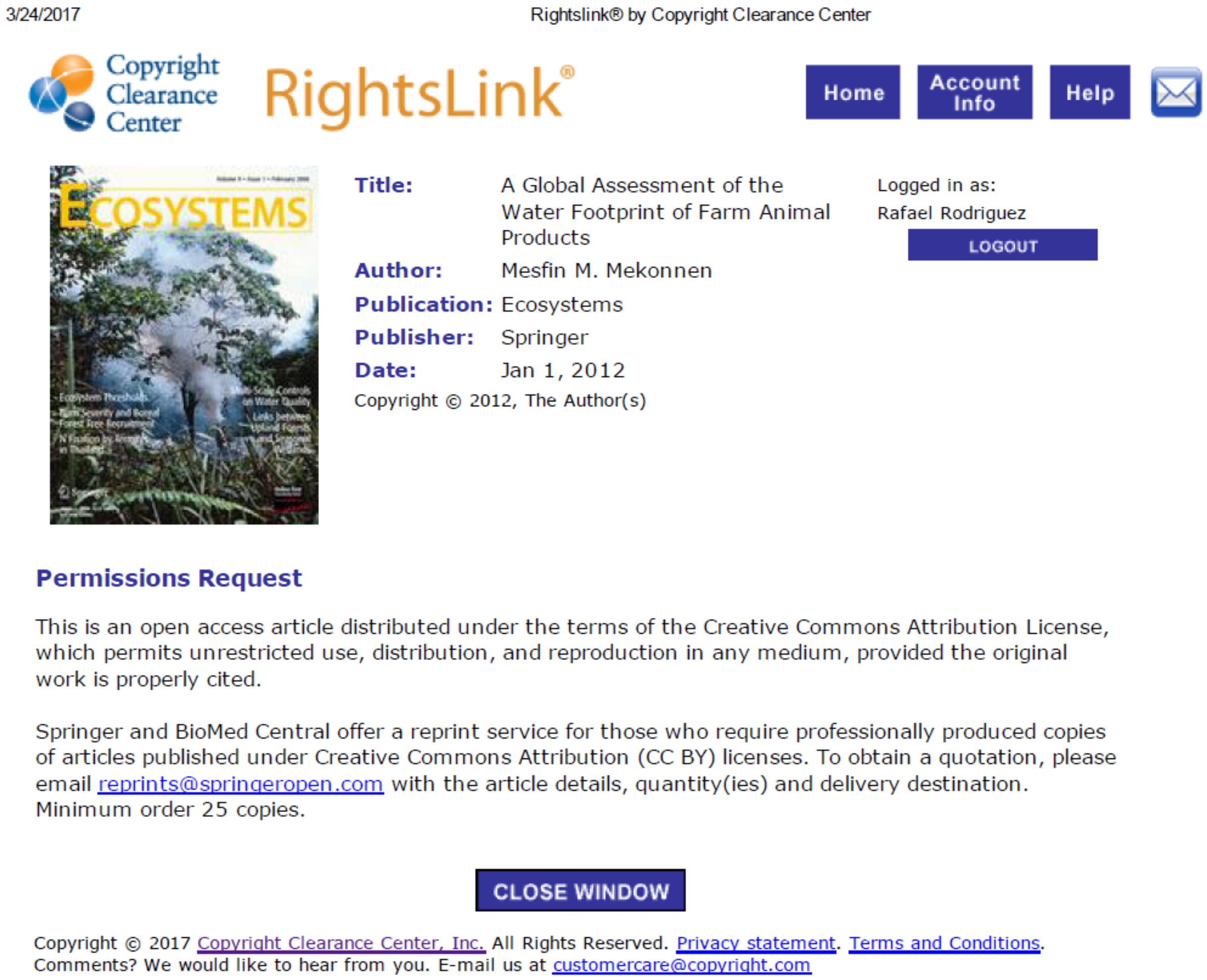

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