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THERMAL CLIMATE IN A DATA CENTER

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DESCRIPTION

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Abstract <p>It is well known thermal climate has a big impact on human wellness. But the influence of thermal climate on equipment is not that well known. In this thesis the question of importance of thermal climate on functioning equipment is considered on example of IT equipment in a data center.</p> <p>The aims of the thesis were to clarify the importance of thermal climate, to find the range of air properties when the equipment is functioning reliably and the ways to achieve this range. The thesis consists of two parts: theoretical and practical ones. In theoretical part, TIA and ASHRAE standards are studied on the optimal range of air properties, white papers of Schneider Electric are studied on air distribution and air cooling systems. In practical part, a functioning data center is studied. Measurements of dry bulb temperature and relative humidity have been done and an analysis was done based on knowledge from theoretical part.</p> <p>As a case study a computer room of five years old functioning data center was chosen. The room had about from 50 to 60 server units and was cooled by two air conditioners. The cool air was distributed by means of raised floor. During functioning, the cooling units almost didn't remove moisture from air. The computer room could be considered as A2 class according to ASHRAE classification because of few locations, where the requirements of A1 class were not followed.</p>			
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1 INTRODUCTION

Thermal climate plays a huge role in creating good indoor environment. Heating, cooling, ventilation and air conditioning systems have been invented in order to maintain air temperature, air humidity and velocity of air at a certain proper level for keeping people feel healthy and comfortable.

But there is also another impact of thermal climate – it is its influence on the functioning of technical equipment in a room, computing equipment in particular. Problem of maintaining good thermal conditions in this case is not trivial at all. Thermal comfort for computing technique means such thermal conditions, in which good functioning of equipment is achieved. There are some limits for temperature caused by special characteristics of this equipment: it can be switched off because of overheating or ‘frosting’. And also there are limits for air humidity in order to save it from corrosion or from electrostatic discharge event.

Data centers, the special purpose rooms, full of constantly functioning computing equipment, are the topic of this thesis. Actuality of the topic can be easily found out in following quotes: “Organizations around the world rely on data centers to house their IT services in a manner that optimizes confidentiality, integrity and availability in support of the entity’s goals. The growth in the number of servers and data centers in the past five years has been nothing short of amazing.” /1, p.10./ “Behind every e-mail, every online transaction, blog and Web page are computer servers operating 24/7. This electronic communication and data storage has become so important that 1,2% of all energy produced in the U.S. in 2005 was consumed by data centers and related infrastructure.” /2, p.7./

The special characteristic of a data center is that its “functioning require no windows, overall lower lighting than in other buildings, and minimal personnel to operate a center. Loads unique or significantly larger than those found in commercial buildings include uninterruptive power supplies (UPS), battery room ventilation, and many step-down transformers.” /3, p.32./

2 AIMS AND METHODS

The aims of this thesis are:

1. To clarify importance of thermal climate on functioning IT equipment of a data center;
2. To find out necessary air properties – environmental recommendations – in a data center for reliable functioning of IT equipment;
3. To elucidate the means of achieving the necessary air properties in a data center;
4. To apply obtained knowledge on practice – to analyze a functioning data center on its efficiency.

The methods used in the thesis are following:

1. To find out the influence of air properties on IT equipment and the processes which happen out of proper environmental conditions;
2. To find and study appropriate literature - data center standards - for researching necessary air properties;
3. To study literature about ways of possible air distribution and cooling as main features of achieving the necessary air properties in space;
4. To investigate a functioning data center on environmental recommendation implementation by means of dry bulb temperature and relative humidity measurements, to study the processes of air distribution and cooling.

The main literature used to study the problems were Telecommunication Industry Association (TIA) data center standard and American Society of Heating, Refrigerating and Air conditioning Engineers (ASHRAE) data center standards, where I took as extracts environmental criterion: dry and wet bulb temperature, relative humidity, dew point, change rate of temperature. Besides the standards I used articles and white papers of ASHRAE, Schneider Electric and some books from MAMK's e-library.

To investigate the data center, measurements were done in following points: inlets and outlets of computer room air conditioning units, inlets and outlets of IT equipment, under the raised floor of computing room. Thereafter certain results were put on Mollier's chart for following analysis and comparison with allowed values from standards.

3 THEORETICAL PART

A data center is a facility used to house computer systems and associated components that perform data processing, storing and distributing functions. Technical components of a data center include: complex of servers, data storage and backup systems, network infrastructure, engineering systems (energy supply, indoor climate control, fire alarm and firefighting systems, etc.) and security system /4/. A typical view of a data center is represented on Figure 1.



FIGURE 1. Servers of a data center /5/

As it is seen from the picture, the quantity of servers that a data center contains is quite big. And as every server consumes electricity, heat is generated, and its amount is only on a rising trend. Heat removal from a data center is a natural reaction on fact that heat accumulation in it leads to IT equipment failures.

To ascertain in establishing adequate thermal climate in space is most serious objective of a HVAC designer while he is elaborating a thermal design of a data center. He must always remember about the strong influence thermal climate (ambient temperature and moisture level, in particular) has on operating envelope of the data center. A scheme of this dependence is performed on Figure 2.

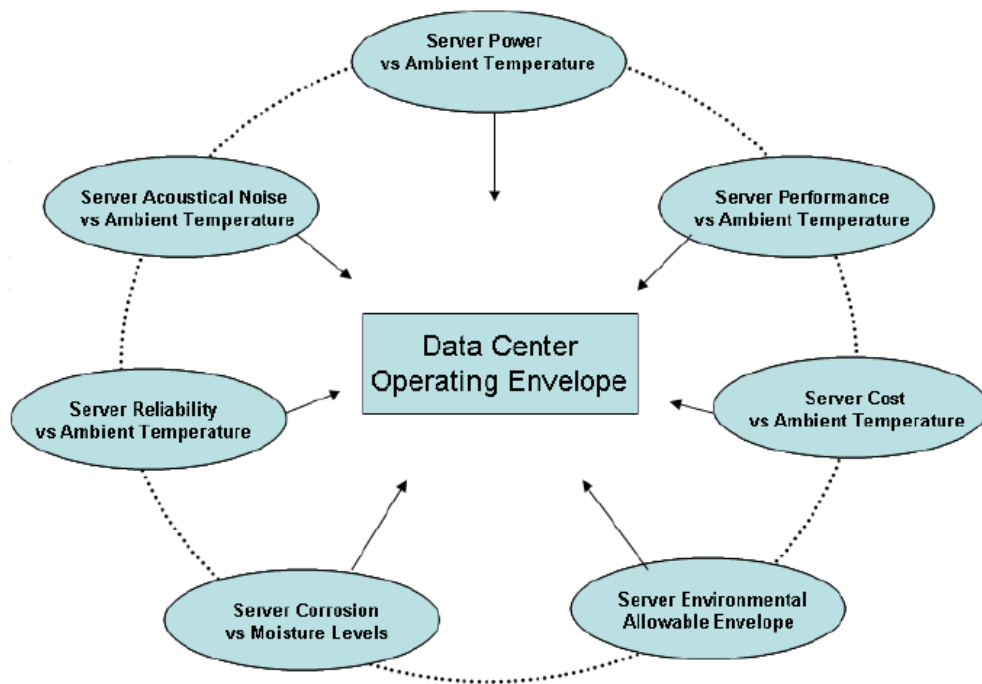


FIGURE 2. Thermal climate influence on operating envelope /6, p.3/

The seven relations represented on Figure 2 will be discussed more wide in following paragraphs. The following information was taken from ASHRAE’s white paper “2011 Thermal guidelines for data processing environments – expanded data center classes and usage guidance” /6/.

The first relation is server power vs ambient temperature. Server power growth can be a reason of fan power growth, component power growth and conversion of both fan and component power. Increased ambient temperature requires bigger flow rate to cool the equipment, so fan power increases with the fan speed increase. Component power increases because of leakage current increase in silicon devices. For example, if a data center is normally operating at server inlet temperature 15°C, then with temperature increase up to 30°C server power consumption will be 4-8% more, and with temperature increase up to 35°C server power consumption will be 7-20% more. The relation between server power and ambient temperature is represented on Figure 3 on example of A2 ASHRAE’s thermal class.

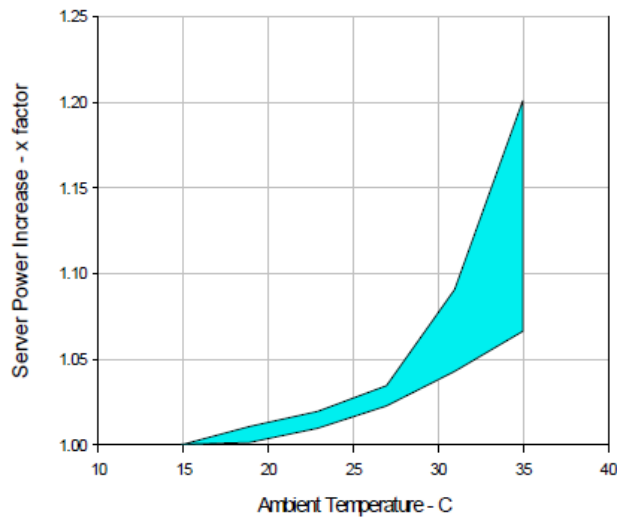


FIGURE 3. Relation between server power and ambient temperature for A2 class /6, p.13/

The second relation is server performance vs ambient temperature. Every IT equipment component has thermal limits which are base for the thermal design power of a data center and cooling equipment selection. If a system designed for certain thermal parameters operates in another, more poor conditions workloads appear and performance degradation can happen.

Server cost vs ambient temperature is the next relation. The poorer thermal parameters a designer chooses for a data center, the harder is to find adequate components. As ambient temperature is higher, there is need in more expensive high-temperature-rated parts for the components which can be not available.

Another relation is server corrosion vs moisture levels. Humidity (moisture) influence on dielectric properties of equipment can cause performance degradation, surface dendrite growth, loss of adhesive strength in dielectric layers. Also condensation causes in servers if a sudden temperature drop happens, which can lead to corrosion of material.

The fifth relation is server reliability vs ambient temperature. Server reliability is measured in hardware failure rate which depends on local climate and type of economization. There are three categories of possible economization: over narrow temperature range (with little or no change to data center temperature; little or no failure caused by temperature impact), expanded temperature range (may be a net increase in

temperatures of some time) and chiller-less (temperature vary over much wider range). The temperature impact on failures in expanded temperature range economization and chiller-less economization is much bigger, but is not the only one source of disturbance.

Server acoustical noise vs ambient temperature is the sixth relation. When ambient temperature raises, the same do cooling requirements for equipment. Using the empirical fan laws (dependence of sound power level and rotational speed) it is possible to get 4 dB increase in noise level with 20% increase of rotational speed. It's impossible to calculate the effect of temperature on noise level, but it is not unreasonable to see e.g. 3-5 dB increase while 2°C (from 25°C to 27°C) temperature rise.

The last relation represented on Figure 3 is server environmental allowable envelope. Although there are standards that distinctly set the recommended envelope, it is not prohibited to go out of these conditions, as long as they are allowable, to utilize economizers as much as possible. /6, p. 13-29./

3.1 Differences in thermal requirements for servers and data centers

Before starting to study thermal climate of a data center one thing should be clear: thermal requirements of a data center totally differ from thermal requirements of a server. And it is very important for both designers of computers and servers cooling and designers of data center cooling to know it in order to create optimal design and reliable data processing environment. Thermal designers of a server typically are given values of Thermal Design Power (TDP) and temperature specifications of each component – Case temperature (T_c) or Junction temperature (T_j), Ambient temperature (T_{ambient}) and Thermal resistance (Θ_{CA}). Besides those cost, weight, volumetric, acoustic characteristics, reliability and quantity of components to cool should be taken into account too while designing. The temperature rise for servers, one of the first parameters discussing by data center thermal designers, is consideration of secondary importance for server thermal designers in the best case. But with all the differences data center thermal designers face a similar list of criterion for designing – cost, performance, reliability characteristics and equipment list. /7, p.38-40./

3.2 Data center standards

Historically first data centers had been created in absence of explicitly defined standards. That had led to a situation where network administrators were forced to choose by themselves technology and its realization in a room with safe and reliable functioning of equipment. For making this process easier some companies, associations and unions started to make researches and create standards to summarize requirements and criterion for a good functioning data center. The standards of two producers are discussed here in more detail:

1. TIA /8/ and
2. ASHRAE TC9.9 /6; 9/

3.2.1 TIA

In April 2005 Telecommunication Industry Association answered network administration's questions and requests by publishing TIA-942, a telecommunications infrastructure standard for data centers /10/.

The standard defines requirements and guidelines for designing and assembling data centers and computer rooms of data centers. It consists of some introductory information like definition of terms and abbreviations, data center design overview and others, it is composed of telecommunication spaces and related topologies specifications like description of typical rooms that a data center consists of and their architectural, environmental, electrical, fire protection and other requirements. Also it consists of information about cabling systems, cabling pathways and redundancy definitions.

Environmental requirements are mainly given for computer rooms. Operational parameters are following: dry bulb temperature ranges from 20°C to 25°C, relative humidity ranges from 40% to 50%, maximum dew point temperature is 21°C, maximum rate of change is 5°C per hour. /8, p.29/.

“The ambient temperature and humidity shall be measured after the equipment is in operation. Measurements shall be done at a distance of 1,5 m above the floor level every 3 to 6 m along the center line of the cold aisles and at any location at the air

intake of operating equipment. Temperature measurements should be taken at several locations of the air intake of any equipment with potential cooling problems.” /8 p.29./

TIA-942 /8/ also gives a link on TIA-569-B standard for air contaminant protection requirements and recommends to keep overpressure inside a data center to prevent infiltration of impurities.

3.2.2 ASHRAE Technical Committee 9.9

All the data for this chapter were taken from ASHRAE’s white paper “2011 Thermal guidelines for data processing environments – expanded data center classes and usage guidance” /6/ and “2008 Environmental guidelines for datacom equipment - expanding the recommended environmental envelope” /9/. It wasn’t possible to work with original standards as they cost quite a lot and no copies were available in libraries of Finland or Saint-Petersburg (to those where I have an access).

Before going deep inside the standards few things must be clarified. The recommended envelope is the limits under which a data center would maintain high reliability and achieve reasonable energy efficient operation. The recommended envelope is a statement of reliability, but its abidance is not mandatory. The allowable envelope is mostly the limits where IT manufacturers examine the equipment for functioning with no failures within the set limits. The allowable envelope is statement of functionality of the IT equipment and it is acceptable to operate in these limits without affecting the overall reliability. Both recommended and allowable conditions relate to IT equipment inlet air.

ASHRAE Technical Committee 9.9 (ASHRAE TC 9.9) engages electronic equipment and systems, technology spaces and critical facilities which include data centers, computer rooms, server rooms, electronic equipment rooms, telecom facilities and others. It was formed in order to achieve good alignment between equipment manufacturers and operation personnel to guarantee proper equipment operation, and so in year 2004 the first publication “Thermal Guidelines for Data Processing Environment” was made. The most important aim was to create a simple and conventional set of environmental guidelines (in conditions of lack any major or firm one) with paying atten-

tion mostly on performance and availability. A Mollier's diagram with the terms of the standard is represented in Appendix 1.

Periodically reviewing available data from IT manufacturers the Technical Committee published new guidelines in 2008. Attention was paid mostly on maintaining high reliability of data centers and energy efficiency increase. The recommended operating envelope was enlarged basing on concurrent data of acceptable IT equipment functioning from IT manufacturers examinations. The new recommended envelope is represented in Appendix 2.

Description and justification of the new envelope will be described below. The temperature limits changed according to successful practice of NEBS GR-63-CORE standard and long history of Central Office installations worldwide. The lower recommended limit was moved from 20°C to 18°C with idea to extend the control range of economized systems (no need anymore to mix hot air with cold to achieve 20°C), but with possibility to increase energy use due to more hours of chiller operation. The upper recommended limit was moved from 25°C to 27°C with idea to increase hours of economizer use per year, but with possibility of IT equipment's power dissipation. The lower moisture limit was moved from 40% of relative humidity (5,5°C dew point temperature at 20°C and 10,5°C dew point temperature at 25°C) to 5,5°C dew point temperature with idea reduce operational costs on humidifying and that it is still not sufficient for ESD effect. The upper recommended limit was moved from 55% of relative humidity to 15°C dew point temperature and 60% of relative humidity with idea providing still adequate guard from corrosion while reducing operational costs on dehumidifying. These differences between previous and new limits are represented in Appendix 3, and the updated 2008 limits themselves are in Appendix 4.

In order to adjust different priorities of IT equipment, new data center classes were elaborated and so a new version of thermal guidelines were published in the whitepaper in 2011 and the book "Thermal guidelines for data processing environments – third edition" appeared in 2012. Two more classes of data center classification were added to allow an operator optimize the operation of a data center in more unbound way with still achieving high energy efficiency and reliability and to adjust different priorities of IT equipment operation. The names of all the classes in classification

were changed as well to avoid the mess. It is possible to see the differences in classifications of the versions 2008 and 2011 in Appendix 5.

The new guidelines haven't change limits of the recommended envelope since previous version. The limits of temperature and humidity of the new classes with the olden classes limits are represented in table 1.

TABLE 1. ASHRAE 2011 Thermal Guidelines /6, p.8/

Classes (a)	Equipment environmental specifications							
	Product operation (b,c)					Product Power Off (c,d)		
	Dry bulb temperature, °C (e,g)	Humidity range, non-condensing (h,i)	Maximum dew point, °C	Maximum elevation, m	Maximum rate of change, °C/hr (f)	Dry bulb temperature, °C	Relative humidity, %	Maximum dew point, °C
Recommended								
A1 to A4	18 to 27	5,5°C DP to 60% RH and 15°C DP	-	-	-	-	-	-
Allowable								
A1	15 to 32	20% to 80% RH	17	3050	5/20	5 to 45	8 to 80	27
A2	10 to 35	20% to 80% RH	21	3050	5/20	5 to 45	8 to 80	27
A3	5 to 40	-12°C DP and 8% to 85% RH	24	3050	5/20	5 to 45	8 to 80	27
A4	5 to 45	-12°C DP and 8% to 90% RH	24	3050	5/20	5 to 45	8 to 80	27
B	5 to 35	8% to 80% RH	28	3050	N/A	5 to 45	8 to 80	29
C	5 to 40	8 to 80% RH	28	3050	N/A	5 to 45	8 to 80	29

- Classes A1, A2, B and C are identical to 2008 classes 1, 2, 3 and 4. These classes have simply been renamed to avoid confusion with classes A1 thru A4. The recommended envelope is identical to that published in the 2008 version.
- Product equipment is powered on.
- Tape products require a stable and more restrictive environment (similar to Class A1). Typical requirements: minimum temperature is 15°C, maximum temperature is 32°C, minimum relative humidity is 20%, maximum relative humidity is 80%, maximum dew point is 22°C, rate of change of temperature is less than 5°C/h, rate of change of humidity is less than 5% RH per hour, and no condensation.
- Product equipment is removed from original shipping container and installed but not in use, e.g., during repair maintenance, or upgrade.

- e. A1 and A2 - Derate maximum allowable dry-bulb temperature $1^{\circ}\text{C}/300\text{ m}$ above 950 m. A3 - Derate maximum allowable dry-bulb temperature $1^{\circ}\text{C}/175\text{ m}$ above 950 m. A4 - Derate maximum allowable dry-bulb temperature $1^{\circ}\text{C}/125\text{ m}$ above 950 m.
- f. $5^{\circ}\text{C}/\text{hr}$ for data centers employing tape drives and $20^{\circ}\text{C}/\text{hr}$ for data centers employing disk drives.
- g. With diskette in the drive, the minimum temperature is 10°C .
- h. The minimum humidity level for class A3 and A4 is the higher (more moisture) of the -12°C dew point and the 8% relative humidity. These intersect at approximately 25°C . Below this intersection ($\sim 25^{\circ}\text{C}$) the dew point (-12°C) represents the minimum moisture level, while above it relative humidity (8%) is the minimum.
- i. Moisture levels lower than 0.5°C DP, but not lower -10°C DP or 8% RH, can be accepted if appropriate control measures are implemented to limit the generation of static electricity on personnel and equipment in the data center. All personnel and mobile furnishings/equipment must be connected to ground via an appropriate static control system. The following items are considered the minimum requirements:
 - 1) Conductive Materials
 - a) conductive flooring
 - b) conductive footwear on all personnel that go into the datacenter, including visitors just passing through;
 - c) all mobile furnishing/equipment will be made of conductive or static dissipative materials.
 - 2) During maintenance on any hardware, a properly functioning wrist strap must be used by any personnel who contacts IT equipment.

The characteristic of the two new classes A3 and A4 are represented on the Mollier's diagram on Figure below with comparison to recommended envelope and previous classes A1 and A2.

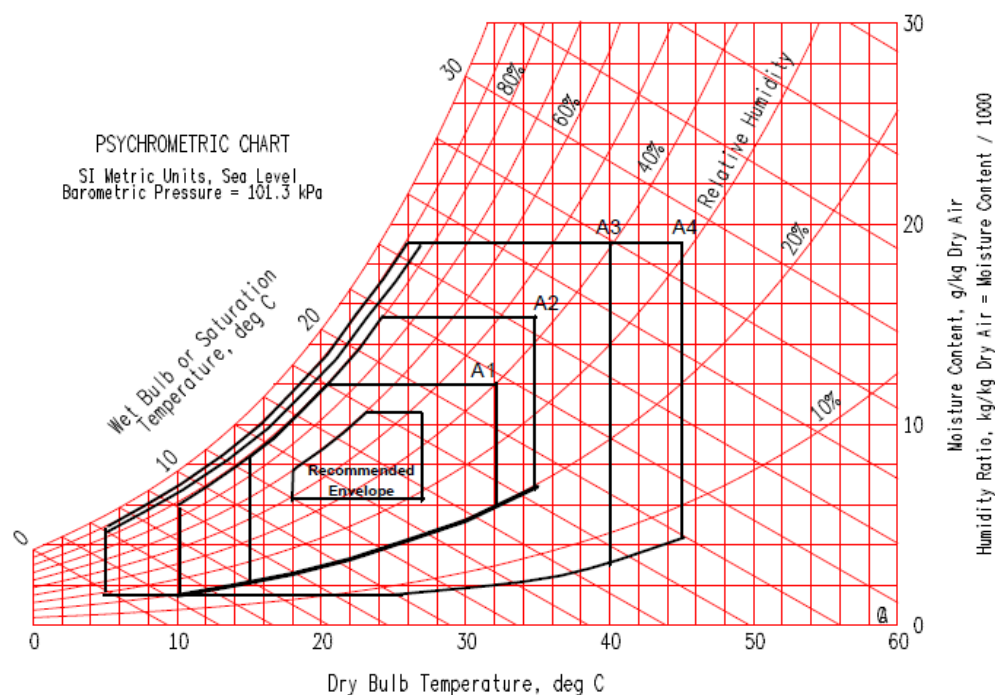


FIGURE 4. 2011 ASHRAE classes for data centers /6, p.9/

Optimization of a data center operation is a complex problem which requires a very detailed evaluation for any changes to be successful. The ASHRAE Technical Committee is not standing aside and is constantly in process of making researches to get information that could relax some of requirements. /6, p.1-10; 9, p.1-8/.

3.3 Humidification features

Air that contains adequate amount of water vapor provides beneficial effects to a data center: it ensures in profitable effect of functioning equipment. Too much or too little water vapor content – humidity of air – contributes to reduced productivity and equipment downtime. The consequences of too high humidity level can be growth of conductive anodic filament on circuit boards and following potential equipment failure, increased risk of corrosion from gaseous contaminants, increased wear on tape devices because of moisture-induced friction. On the other hand, the consequence of too low humidity level besides electronic components destruction on circuit board is increased risk of electrostatic discharge (ESD) effect possibility. /11, p.49./

The circumstances that change air humidity are infiltration, condensation and ventilation. The effect of infiltration can be described by following: if one room's humidity level differs from other's one, the levels will always try to equalize; the rate of this equalization depends on amount of open spaces, humidity levels difference and temperatures in rooms. The effect of condensation can be described by following: when warm air passes through a cooling coil with very low temperatures of cooling liquid (6-9°C), water vapor contained in the air condensates on the coil, and outcoming air becomes drier. The effect of ventilation can be described by following: supply of fresh air to all the rooms is required to provide employees with oxygen and fresh air; the indoor air changes due to the mix with fresh air that has other parameters. /12, p.4./ Therefore humidifiers and dehumidifiers are applied to maintain needed environment. There are several types of humidifiers (steam, infrared, ultrasonic, direct) which can be placed in air handling units or in ducts. Typically, humidity is controlled by relative humidity sensors. /11, p.50-52./

Humidity control system besides investment and installation costs (humidifier, pipes, drains, etc.) has quite big operational costs (e.g. water and energy consumption). The second drawback is that most common commercially available humidity transmitters

mostly can't meet manufacturer's printed statement of accuracy. That was found out by laboratory and fields tests of the National Building Controls Information Program (NBCIP). "The deviations measured were in exceed of 24% of error over a significant portion of the test." With the help of NBCIP study it became clear that control sensors are not always able to control humidity and thereby CRAH-units can just fight each other (some of sensors give command to humidify, and others – to dehumidify at the same time in the same room). So if a humidification system must be, its control should be based on high quality dew point sensors. As measurements of any data center show, relative humidity varies a lot in space while dew point temperature is relatively constant. /11, p.53./

In theory, the purpose of humidification is to improve reliability of a data center, but in practice it is mostly only source of problems. Electrostatic discharge association (ESDA) excluded humidification as a primary control for preventing ESD effects. In their opinion the starting point of destructive charge range is so low that humidification only can't prevent it. There is a test on ESD immunity with procedures from Standard IEC61000-4-2: "each piece of IT equipment is tested using a calibrated probe that generates up to 8000V in contact discharge and 15000V in air discharge /8, p.49/." Their work experience gave them two main conclusions. The first one is that "the charge levels from personnel under normal conditions of data center grounding are unlikely to exceed those already tested for in IEC61000-4-2 for the CE Mark, under any condition of relative humidity /11, p.49/." The second one is "if personnel are handling circuit board or components, the threshold levels for ESD damage are so low (<100V) that humidification has no beneficial effect /11, p.49/."

Is humidity control that much important as it is described in standards? Nowadays there are several data centers functioning without it (mostly in order to reduce operational costs and save budget). Not that long time ago a few studies of IT equipment operating with no air conditioning were published. The first published experiment was realized from November 2007 to June 2008 in USA, Washington State. The computing equipment was functioning in a tent. "Although a fence knocked into the tent during a storm, water dripped on the racks, and leaf was sucked into a server, the authors of this study noted "zero failures, or 100% uptime"/11, p.53/." Another experiment was made for more than 10 months period in New Mexico. It was a comparison between two data centers, one fully conditioned and another only with air-side econo-

mizer and filtration (no cooling). By the end of experiment considerable variations of temperature and humidity in the data center with no cooling were the conclusion of study, but failure quantity did not increase significantly. The persons in charge for this experiment offered an opinion that this experience can be used also in future high density data centers. One more published experiment was done during one year period in San Francisco Bay Area. The data center was designed with a humidifier, but during its functioning there were a lot of problems with it. And so they switch the humidifier off to test functioning without active humidity control. After turning it off no IT equipment failures due to low humidity were noticed. /11, p.53-54./

In order to dispose of the intricate question about humidification need ASRAE created a research project on the effects of low moisture environments on IT equipment. The project was supposed to occur during 2012-2013 and provide some information about feasibility of current humidification requirements. /6, p.9-10./

The choice of placing humidity control in a data center or not is a quite complicated question and has no common answer as every data center is unique. A designer must think about many things before making his choice like: level of reliability of functioning data center, installation and operational costs of humidification system, alternative ways to reduce ESD effect opportunity, quantity of lost money during downtime due to a breakdown, climate of location area and how it changes during seasons and etc. Only after taking into account all the factors the designer can make a choice.

3.4 Studying HVAC-systems

“Cooling is driven by power consumption and itself consumes power”; “In many respects, we can view cooling as a function of power consumption. As power consumption rises, so do cooling demands and the power consumption associated with that cooling.” /1, p.41./

A general rule is that a CRAC system rating must be 1.3 times the anticipated IT load rating plus any capacity added for redundancy. For larger data centers, the cooling requirements alone are typically not sufficient to select an air conditioner. Typically, the effects of other heat sources such as walls and roof, along with recirculation, are significant and must be examined for a particular installation. The design of the air

handling ductwork or raised floor has a significant effect on the overall system performance, and also greatly affects the uniformity of temperature within the data center. The adoption of simple, standardized, and modular air distribution system architecture, combined with the simple heat load estimation method described, could significantly reduce the engineering requirements for data center design. /13, p.6./

According to Schneider Electric's White Paper #25 /13/, it is possible to predict the heat load of a data center quite reliably. The main idea is that total heat output equals to the sum of component heat outputs. The estimation covers total load power of IT equipment, UPS power system, power distribution system, lightning and amount of people that can be inside at the same time. The parameters are determined through simple and standardized rules. The most valuable advantage of the estimation is that the values can be got quickly and by a person without special knowledge. The paper form of the method – heat output calculation worksheet – is represented on Figure 5.

Item	Data required	Heat output calculation	Heat output subtotal
IT equipment	Total IT load power in Watts	Same as total IT load power in watts	_____ Watts
UPS with battery	Power system rated power in Watts	$(0.04 \times \text{Power system rating}) + (0.05 \times \text{Total IT load power})$	_____ Watts
Power distribution	Power system rated power in Watts	$(0.01 \times \text{Power system rating}) + (0.02 \times \text{Total IT load power})$	_____ Watts
Lighting	Floor area in square feet, or Floor area in square meters	$2.0 \times \text{floor area (sq ft)}$, or $21.53 \times \text{floor area (sq m)}$	_____ Watts
People	Max # of personnel in data center	$100 \times \text{Max \# of personnel}$	_____ Watts
Total	Subtotals from above	Sum of heat output subtotals	_____ Watts

FIGURE 5. Data center heat output calculation worksheet /13, p.3/

To avoid misunderstandings in characteristics of Figure 5, here are some explanations.

“Total IT load power in Watts - the sum of power inputs of all the IT equipment.

Power system rated power - the power rating of the UPS system. If a redundant system is used, do not include the capacity of the redundant UPS.” /13, p.3-4./

3.4.1 Air distribution

“The primary distinctions that determine the effectiveness of a data center cooling system are rooted in the air distribution /14, p.3/.” Airflows are only straitened by construction of a room, so controlling them is very important, because the main aim for air distribution in a data center is to separate exhaust air from intake air of IT equipment to prevent it from overheating. This separation significantly increases efficiency of cooling system. /14, p.5./

According to Schneider Electric's White Paper #55 /14/ classification, there are three basic methods to distribute air in a data center: flooded, targeted and contained ones. In flooded method the only limitation of air flow is made by room's walls, ceiling and floor, which leads to heavy mixing of supply and return flows. In targeted method a duct or other mechanism directs airflows within three meters of IT equipment inlet and outlet. In contained method the airflows are enclosed to completely eliminate any mixing.

Each of methods can be used for supply or/and return airflow, which means that there are nine possible combinations of air distribution with different costs, performance, capabilities and benefits. The proper implementation of the combinations of air distributions, represented on Figures 6 and 7, is the basic knowledge for data center personnel.

Cooling units can be located on perimeter (traditional room-based cooling implementation) or outdoors and in row (non-traditional implementation). Traditional room-based cooling implementations, represented on Figure 6, can't always be fit for maximum power densities (kW per rack). Non-traditional implementations are becoming more popular in data centers nowadays. A general rule of Figures 6 and 7 is that so air distribution complexity, costs and power density facility is the lowest in left upper corner and they increase while going to right and down until the biggest in right nether corner.

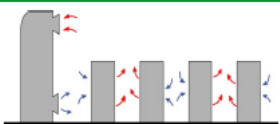
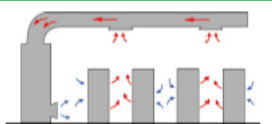
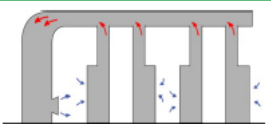
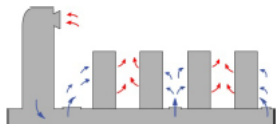
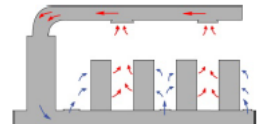
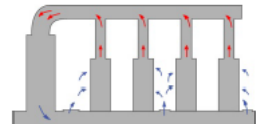
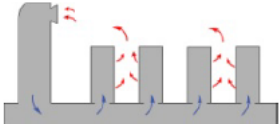
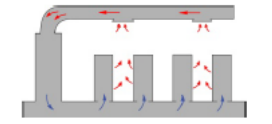
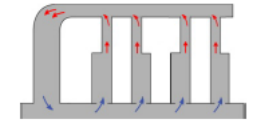
	Flooded return	Targeted return	Contained return
Flooded supply	 <p>Small LAN rooms < 40kW Not recommended for most data centers Low cost, simple installation Least energy efficient of all air distribution architectures because 100% of the cold supply air is allowed to mix with hot return air. Supply air temperature extremely unpredictable above. Distribution type can cool up to 3kW per rack</p>	 <p>General use Not recommended for most data centers Low cost, ease of install More energy efficient than flooded return since 40-70% of IT hot exhaust air is captured and delivered back to the cooling unit. Supply air more predictable than flooded supply since less hot air is allowed to mix with cold supply air. Distribution type can cool up to 6kW per rack</p>	 <p>Large data center / colocation Upgradeable (vendor specific) Most energy efficient of all air distribution architectures since it allows increased cooling unit supply temp resulting in increased economizer hours. 70-100% of IT equipment hot exhaust air is captured and delivered back to the cooling unit. Supply air is most predictable since no hot air is allowed to mix with cold supply air. Distribution type can cool up to 30kW per rack</p>
Targeted supply	 <p>Data centers with static power densities Not recommended for new designs – unable to keep up with power density projections More energy efficient than flooded supply since more IT equipment hot exhaust air is diverted back to the cooling unit. Distribution type can cool up to 6kW per rack</p>	 <p>Small to medium data centers More energy efficient than flooded return since 60-80% of IT equipment hot exhaust air is captured and delivered back to the cooling unit. Supply air more predictable since less hot air is allowed to mix with cold supply air. Distribution type can cool up to 8kW per rack</p>	 <p>Hot spot problem solver Upgradeable (vendor specific) More efficient than targeted supply and return since 70-100% of IT equipment hot exhaust air is captured and delivered back to the cooling unit. Supply air is most predictable since no hot air is allowed to mix with cold supply air. Allows increased cooling unit supply temp resulting in increased economizer hours. Distribution type can cool up to 30kW per rack</p>
Contained supply	 <p>Mainframes / racks with vertical airflow More energy efficient than targeted supply but less efficient than contained return. Containing the supply air, forces the rest of the room to become the hot aisle which limits the number of economizer hours. Supply air is more predictable since little hot air is allowed to mix with cold supply air. Distribution type can cool up to 30kW per rack</p>	 <p>Mainframes / racks with vertical airflow More energy efficient than targeted supply but less efficient than contained return. Containing the supply air, forces the rest of the room to become the hot aisle which limits the number of economizer hours. Supply air is most predictable since no hot air is allowed to mix with cold supply air. Distribution type can cool up to 30kW per rack</p>	 <p>Harsh non-data center environments Slightly less efficient than contained return with flooded or targeted supply - requires more fan energy. Allows increased cooling unit supply temp resulting in increased economizer hours. Distribution type can cool up to 30kW per rack</p>

FIGURE 6. The nine combinations of air distribution (traditional room-based cooling implementations) /14, p.4/

A common power consumption of a rack in a data center is about 3 kW per rack, but some racks can be customized up to 30 kW per rack. The flooded method due to absence of air flow limitation and possibility of supply and return flows heavy mixing is considered as method with least cooling capability. The targeted method is considered to have more cooling capability than the flooded method, but less than the contained one. Contained supply or contained return is used to cool racks with power densities 5...15 kW in general. And as these power densities are only a small part of all racks in data center, the contained method is combined with flooded or targeted methods, which allows data center to be designed on average power density of this data center,

and be able to adapt for peak power density racks. The ‘pure’ contained method – contained supply and contained return – is not recommended to use because of high costs of the system with absence of additional benefits, excluding cases where a complete isolation of racks is required to protect equipment from harsh environment. /14, p.3-8./

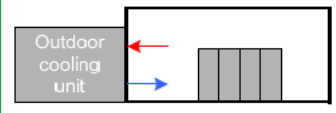
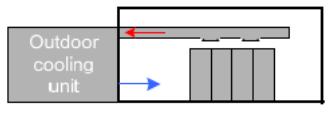
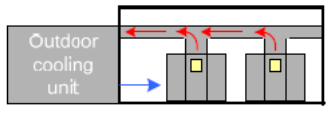
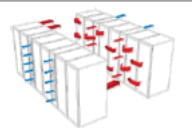
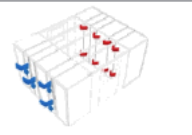
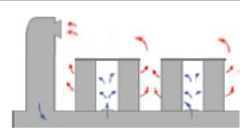
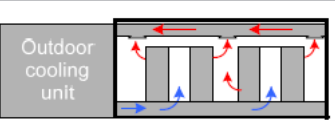
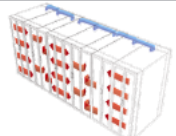
	Flooded return	Targeted return	Contained return
Flooded supply	 <p>Hard floor, cooling unit located outdoors Not recommended for most data centers. Not effective because air mixing prevents predictable IT inlet temperatures.</p>	 <p>Hard floor, cooling unit located outdoors Not recommended for most data centers. Not effective because air mixing prevents predictable IT inlet temperatures.</p>	 <p>Hard floor, cooling unit located outdoors Recommended for new data centers. Variable speed fans on cooling units controlled by IT temperature.</p>
Targeted supply	<p>No non-traditional alternative</p>	 <p>Hard floor, row-based cooling units Recommended for data centers below 1MW. Variable speed fans on cooling units controlled by IT temperature.</p>	 <p>Hard floor, row-based cooling units Recommended for data centers below 1MW. Variable speed fans on cooling units controlled by IT temperature.</p>
Contained supply	 <p>Raised floor, perimeter cooling units Not recommended for new data centers. Good solution for existing data centers. Variable speed fans on cooling units controlled by pressure and active tiles controlled by IT temperature.</p>	 <p>Raised floor, cooling unit located outdoors Targeted return doesn't add much value since supply is contained therefore not recommended. Variable speed fans on cooling units controlled by pressure and active tiles controlled by IT temperature.</p>	 <p>Hard floor, row-based cooling units Only recommended for harsh environments or existing data centers where complete containment is required for a single row of racks (e.g. squeezing a row into an existing hot aisle). Variable speed fans on cooling units controlled by IT temperature.</p>

FIGURE 7. The nine combinations of air distribution (non-traditional implementations) /14, p.5/

3.4.2 Cooling systems

The simplest explanation why we need cooling is: when temperature of IT components rises, so does equipment failure possibility. According to Svante Arrhenius law applied for IT sphere “for each 10°C rise in temperature, the component failure rate will be double /1, p.41/.”

According to Schneider Electric’s White Paper #59 /15/ there are thirteen basic methods of removing heat from IT equipment. The following Figure 8 shows these methods.

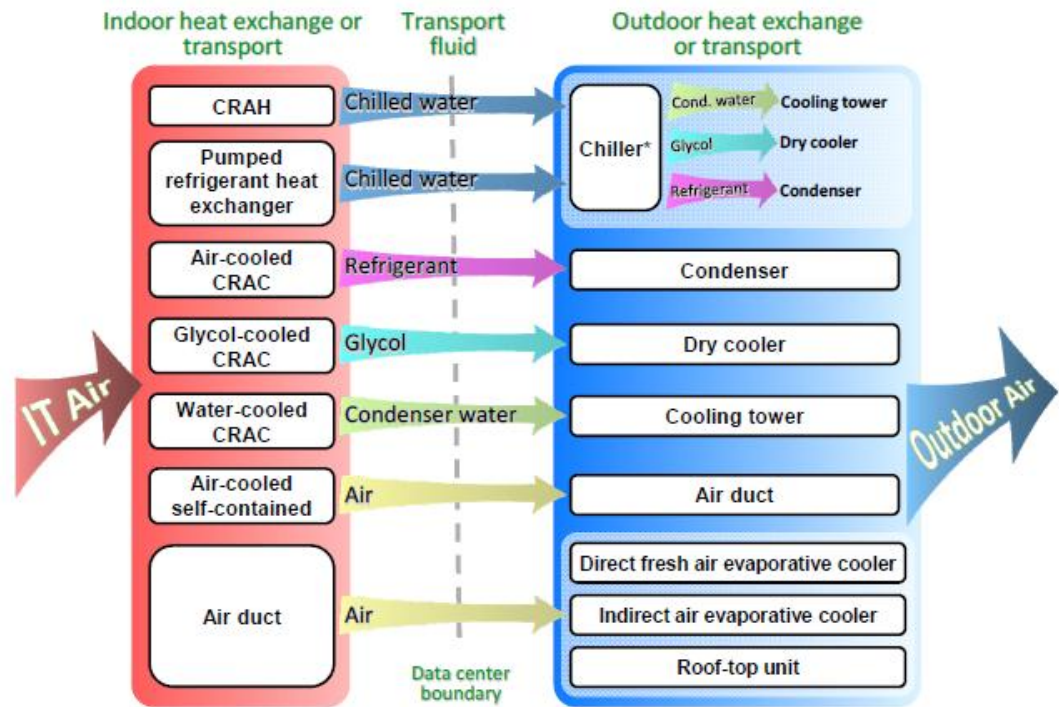


FIGURE 8. Simplified breakdown of the thirteen fundamental heat removal methods /15, p.3/

Eleven of them rely on the refrigerator cycle while the others rely on outdoor conditions. The methods are discussed wider in following chapters./15, p.3./

3.4.2.1 Chilled water systems

The first three ways to cool a data center are to use chilled water system. Indoor heat exchange happens in a computer room air handler (CRAH). The heat is transported out of IT environment by means of chilled water. The outdoor heat exchanger is a chiller. If the chiller uses condenser water it is called cooling tower. If the chiller uses glycol it is called dry condenser. And if the chiller uses refrigerant it is called condenser. /15, p.3-4./

The principal scheme of system which uses cooling tower as chiller (fluid is condenser water) is represented on Figure 9. It functions in a following way: the computer room air is cooled down by going through a coil in the CRAH with the chilled water. The temperature of chilled water is usually about 8-15°C. After the CRAH warmed water goes to the water chiller (chilled water – condenser water heat exchanger) and

gives received heat to another circulating water system, so called condenser water loop. Water in this another system cools down in a water tower which is located on a roof of the building. In the water tower there is a fill material (sponge-like) and a fan that increase and accelerate evaporation, and so cool the condenser water in the system. /15, p.3-4./

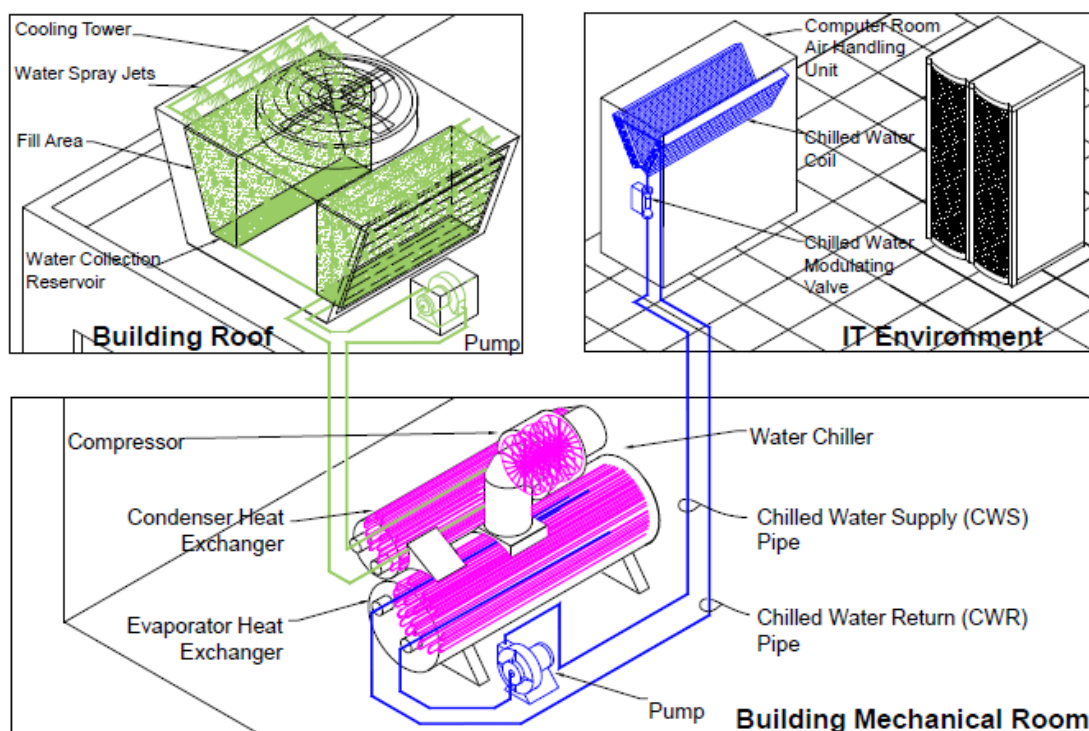


FIGURE 9. Water-cooled chilled water system /15, p.4/

Following issues can be named as advantages of the methods: efficiency of the chilled water system grows up with increasing capacity of a data center; chilled water CRAH units cost not that much compared to others; water loops easily run big distances; the system can be combined with economizer for efficiency increasing. The disadvantages of the chilled water system are: the method gives additional pipes with water to an IT environment; typically the method has the highest capital costs when data center is less than 100 kW of electrical IT loads. The method is used mostly for data centers with capacity at least 200 kW. Condenser loops and water towers are usually used not only by computer rooms – they are components of a larger cooling system of the whole building. /15, p.4-5./

3.4.2.2 Pumped refrigerant for water systems

The next three ways of cooling is called pumped refrigerant for water systems. Indoor heat exchange happens in an air handler. The heat is transported out of IT environment by means of refrigerant. The outdoor heat exchanger is a chiller. The chiller can use condenser water, glycol and refrigerant. /15, p.6./

A schematic drawing of a system is represented on Figure 10. The systems functions in a following way: the computer room air is cooled down in a same way as in previous case. An indoor air cooling unit is linked with a chiller by means of heat exchanger that separates two loops – one with chilled water and another with oil-less refrigerant or non-conductive fluid. A pump is used in refrigerant loop because of high density of the fluid, but there is no compressor in the loop. /15, p.6./

Advantages of the methods are: no water loops near IT equipment; application of refrigerant eliminates risks of damage in case of leakage; cooling system works efficiently because of very close location to servers. Main disadvantage of the methods is that the investment costs are high (because of heat exchanger and pumps). As the method is based on direct cooling of servers, it is mostly used for high density row or rack cooling of IT equipment and systems that are closely coupled to it. /15, p.6./

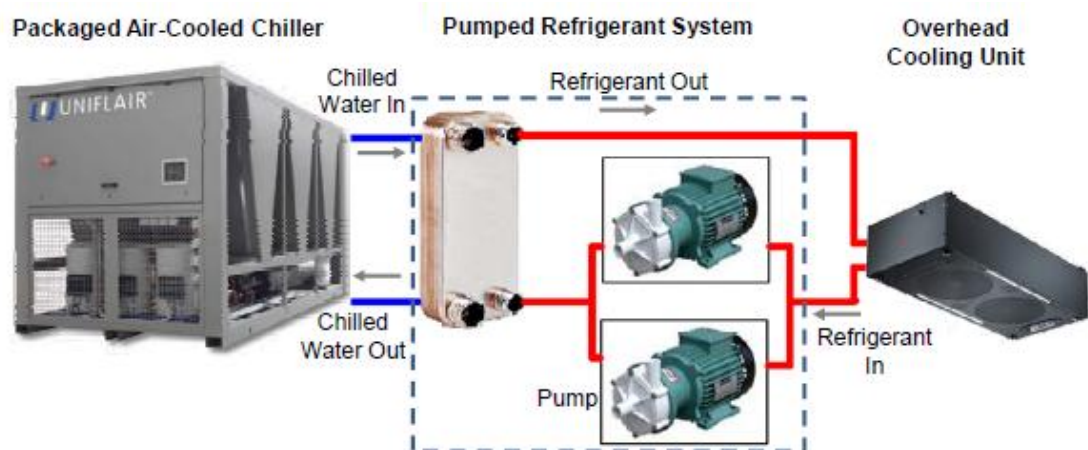


FIGURE 10. Schematic drawing of a pumped refrigerant system connected to chilled water /15, p.6/

3.4.2.3 Air cooled CRAC DX system

The seventh method is known as air cooled CRAC DX system, where “DX” means direct expansion. Indoor heat exchange happens in evaporator coils of a computer room air conditioner (CRAC). The heat is transported out of IT environment by means of refrigerant. The outdoor heat exchanger is a condenser. /15, p.7./

The principal scheme of system is represented on Figure 11. There is only one refrigerant loop in the system. Evaporator coils, compressor and expansion valve are placed indoors in CRAC, condenser is located outdoors. /15, p.7./

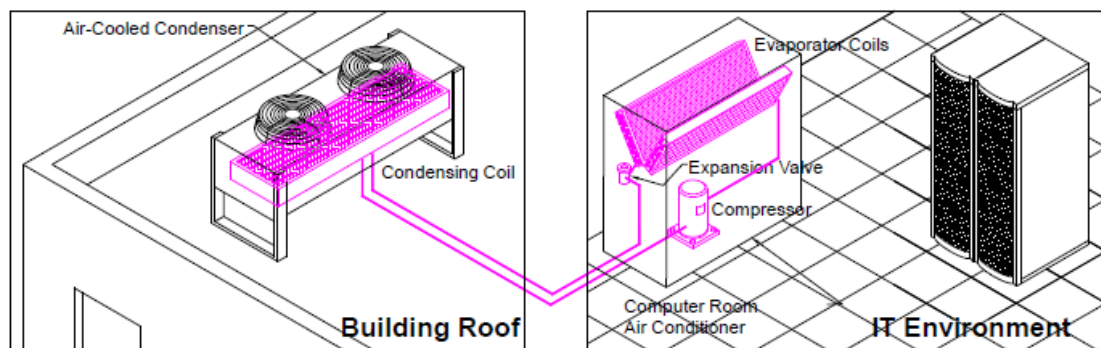


FIGURE 11. Air-cooled DX system /15, p.7/

Advantages of the method are: very low overall costs; ease of maintaining the system. Disadvantages are: only properly designed and installed piping system can give reliable performance; other air conditioners can't be attached. The system is mostly used in 7-200 kW data centers, computer rooms and wiring closets with medium content of requirements. /15, p.7./

3.4.2.4 Glycol-cooled system

The eighth method is called glycol-cooled system. Indoor heat exchange happens in evaporator coils of a computer room air conditioner (CRAC). The heat is transported out of IT environment by means of glycol. The outdoor heat exchanger is a dry cooler. /15, p.8./

The principal scheme of system is represented on Figure 12. The systems functions in a following way: the computer room air is cooled down in evaporator coil of a CRAC. A condensing coil is replaced with a heat exchanger, so glycol loop cools down re-

frigerant loop there. All the components of refrigerant cycle are located in CRAC, and dry cooler with a pump of glycol loop are located outdoors. /15, p.8./

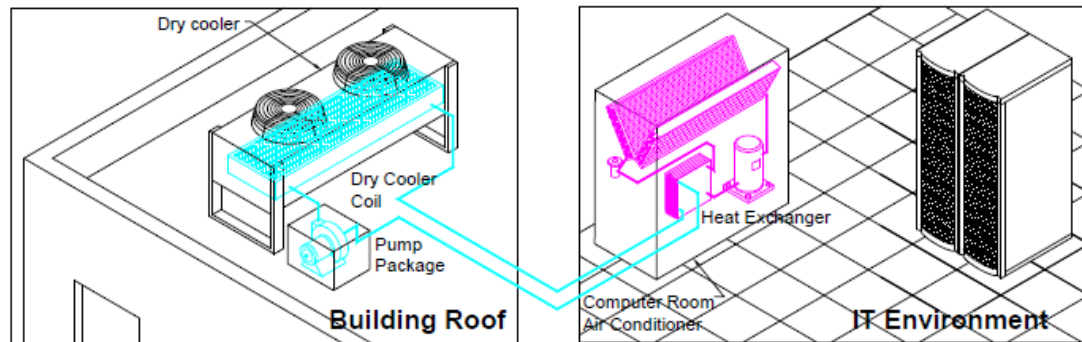


FIGURE 12. Glycol-cooled system /15, p.8/

Advantages of the method are: all the refrigerant system is manufactured in a CRAC unit in a factory which means very high reliability; glycol pipes can serve several cooling units (because they can run longer distances compared to refrigerant lines); if there is an economizer joined to the system and the outdoor temperatures are low, glycol lines can run bypass the heat exchanger directly to the economizer to do free cooling of IT equipment which reduces operational costs a lot. Disadvantages are: capital and installation costs are increased due to additional components – pump package, valves, etc.; taking care about glycol volume of the system is required; it is additional source of liquid in data center. The method is used in 30 – 1000 kW data centers and computer rooms with medium content of requirements. /15, p.8-9./

3.4.2.5 Water-cooled system

The next method is water-cooled system. Indoor heat exchange happens in evaporator coils of a computer room air conditioner (CRAC). The heat is transported out of IT environment by means of condenser water. The outdoor heat exchanger is a cooling tower. /15, p.9./

The principal scheme of system is represented on Figure 13. The systems functions in a very similar to glycol-cooled system, although the main differences are following: water is used instead of glycol and cooling tower is used instead of dry cooler. /15, p.9./

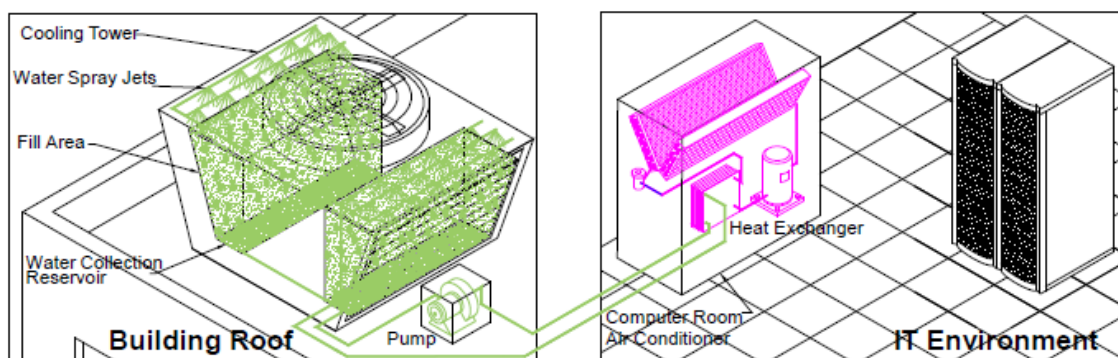


FIGURE 13. Water-cooled system /15, p.9/

Advantages of the method are: all the refrigerant system is manufactured in a CRAC unit in a factory which means very high reliability; condenser water pipe loop easily run long distances and that is why they serve few cooling equipment at the same time; using condenser water is much cheaper than chilled water. Disadvantages are: initial costs are high due to additional equipment – cooling tower, pump, etc.; there are rather high maintenance costs; it is additional source of liquid in IT environment; a cooling tower used to cool all the building can be less reliable compared to one used only for data center. The method is mainly used in 30 kW and more data center with medium-large content of requirements in conjunction with other building systems. /15, p. 9-10./

3.4.2.6 Air-cooled self-contained system

The tenth method is known as air-cooled self-contained system. Indoor heat exchange happens in evaporator coil. The heat is transported out of IT environment by means of air ducts. /15, p.10./

The principal scheme of system is represented on Figure 14. The systems functions in a following way: All the IT equipment components that need to be cooled are located in one enclosure together with an evaporator coil. Cool outdoor air comes in the coil by means of an inlet duct. Air drawn through condensing coil becomes exhaust air and is rooted to outdoors. /15, p.10./

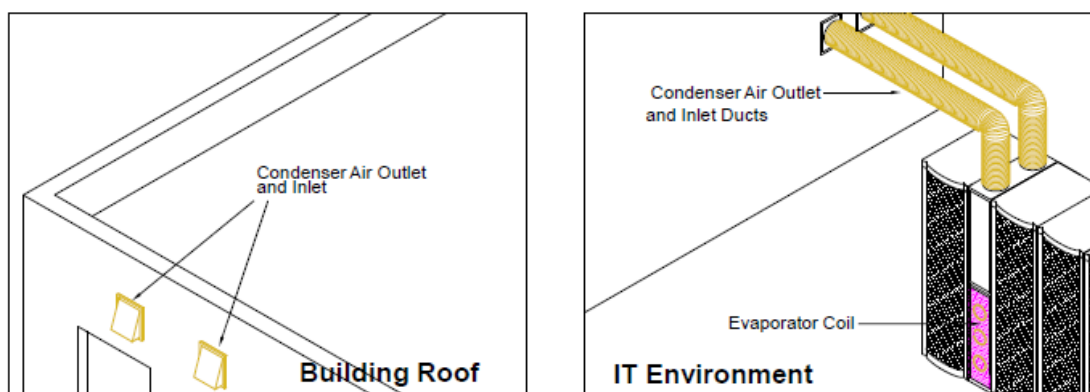


FIGURE 14. Indoor air-cooled self-contained system /15, p10/

Advantages of the method are: installation costs are the lowest; refrigeration cycle components are factory sealed. Disadvantages are: removal heat capacity is not too big; air moving requires ductworks or dropped ceiling; if system management is connected to whole building problems can appear with its switching off during weekends. The method is mostly used wiring closets, laboratory environments; computer rooms with medium content of requirements; to eliminate hot spots in a data center. Usually system's capacity is limited up to 15 kW otherwise cooling equipment will require too much space. Systems with outdoor outlets of exhaust air are not commonly used for precision cooling applications. /15, p. 10-11./

3.4.2.7 Direct fresh air evaporative cooling system

The eleventh method of cooling is called direct fresh air evaporative cooling. As it represented in the name of method, the cooling of equipment is done by outdoor air without heat exchanger and additional transport fluid. Although filters are used they don't guarantee total removal of contaminants from air. The principal scheme of system is represented on Figure 15. The system uses fans and louvers to regulate amount of outdoor air coming to the filter and amount of exhaust air coming outdoors and for recirculation. The heat removal of outdoor air is done with evaporative cooling – by means of wet mesh material. This increases data center humidity and minimizes effectiveness of the method. /15, p.11./

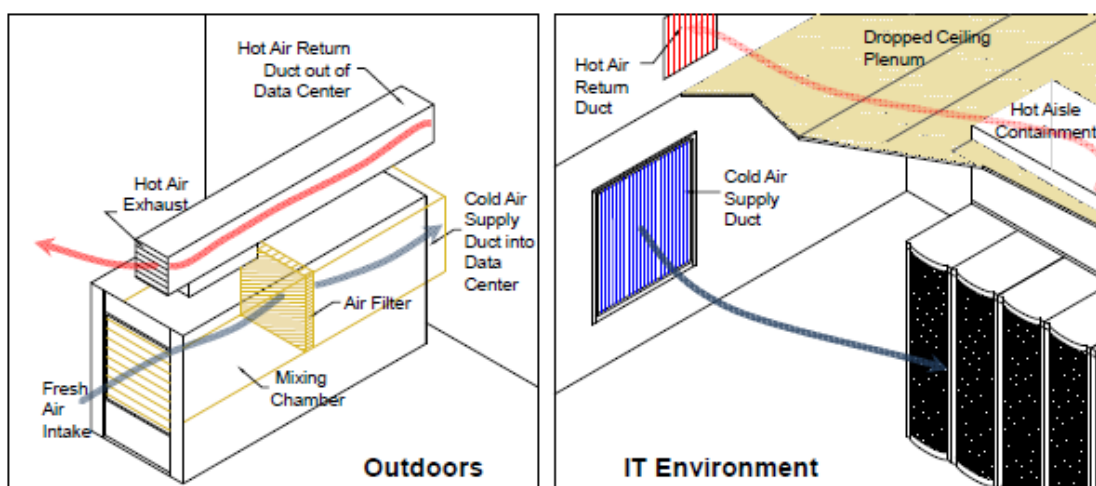


FIGURE 15. Example of direct air evaporative cooling system /15, p.12/

Advantages of the method are: cooling equipment is collated outside of data center which provides more efficient use for IT equipment; there is a big benefit for a dry climate located data centers using this method (about 75% economy) compared to methods without free cooling. Disadvantages are: there are difficulties in changing system to this in existing data center; too frequent change of filters can be required in areas with poor outdoor air quality; big amount of humidity is delivered to data center. Usually this method is used for high power density data centers (1000 kW and more). /15, p.12./

3.4.2.8 Indirect air evaporative cooling system

The method is called indirect evaporative cooling. Compared to previous method, data center air is isolated from outdoor air. When the temperatures of inlet air to data center are higher than they should be, fans blow outdoor air to air-to-air heat exchanger for indirect cooling it down. Heat exchangers can be of plate or rotating type. For cooling outdoor air water spraying is used. The principal scheme of system is represented on Figure 16. /15, p.12./

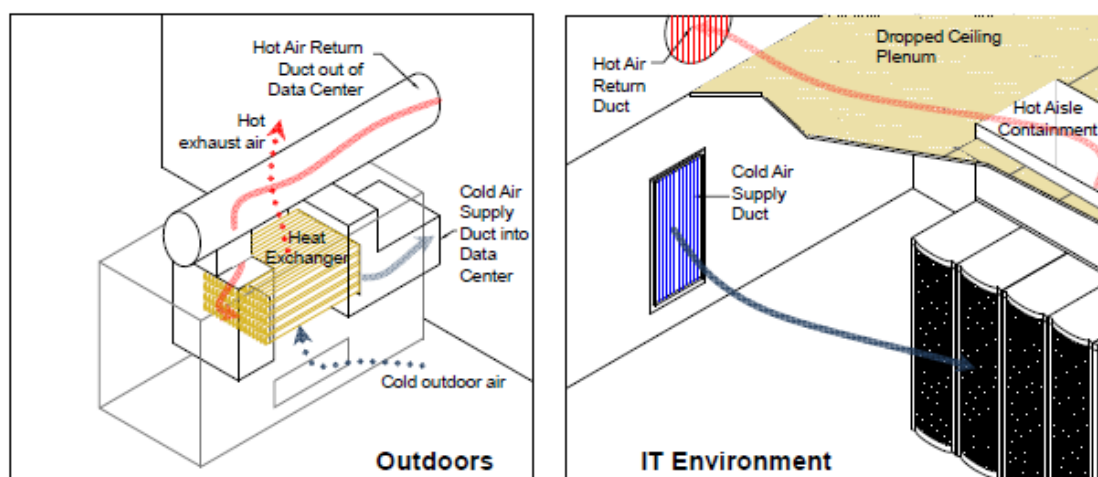


FIGURE 16. Indirect air economizer system /15, p.13/

Advantages and disadvantages of the method are quite similar to previous method, direct air evaporative cooling system. The method is used for high power density data centers (1000 kW and more). /15, p.13./

3.4.2.9 Self-contained roof-top system

The last, thirteenth method is called self-contained roof-top system and is not typically used for modern data centers. Principals are basically the same as for previous method except for the fact that complete units are located outdoors, mounted on roof and are larger. /15, p.14./

Advantages of the method are: cooling equipment is collated outside of data center which provides more efficient use for IT equipment; there is a big benefit for a mild climate located data centers using this method compared to methods without free cooling. Main disadvantage is that there are difficulties in changing of existing cooling system to this in existing data center. The method can be applied for data centers that are part of mixed-use facility. /15, p.14./

4 PRACTICAL PART

The purpose of practical part was to apply obtained knowledge from theoretical part on practice – to analyze a functioning data center on its efficiency. A data center was chosen for investigation on environmental recommendation implementation. Measurements of dry bulb temperature and relative humidity were done in certain locations

in order to find out the class of the data center according to ASHRAE/6/. The processes of air distribution and cooling in the data center were studied. Basing on gotten results, some conclusions about performance and efficiency of cooling system of the data center were done, so that it could help HVAC crew with improving it.

4.1 Description of study case room

As case study a computer room of five years old data centers has been chosen. The computer room has about from 50 to 60 server units. The dimensions of the room are: length 17,83m, width 4,89m and height 2,96m, so the volume is about 258m^3 . Real dimensions can differ a bit because these values were got by tape-measuring in field conditions. A sketch of the data center computer room made in AutoCAD 3D modeling is shown on Figure 17.

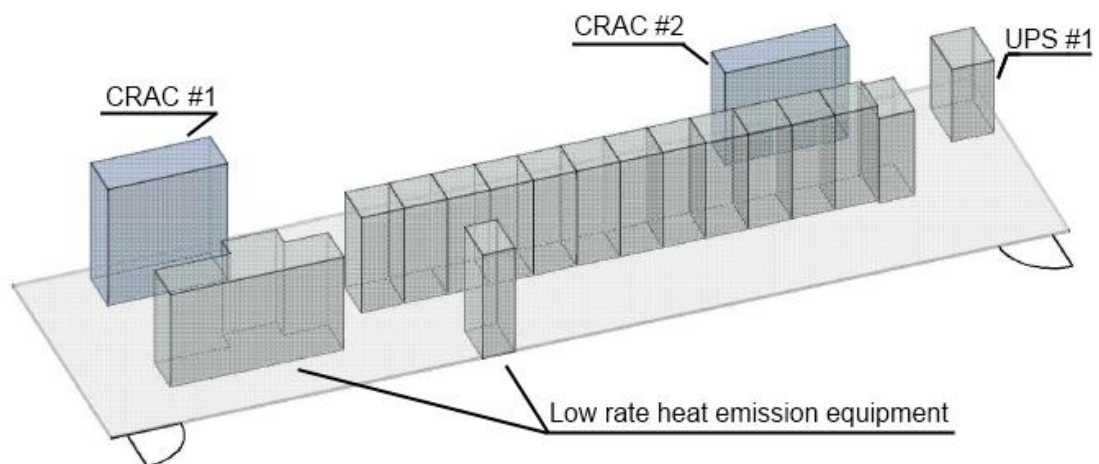


FIGURE 17. AutoCAD model of study case room of the data center

An infrastructure of a data center normally consists of following parts: power system and uninterruptive power supply (UPS) system, cable network, HVAC system, fire alarm system, fire suppression and smoke removal systems, access control system.

The uninterruptive power supply system is performed in the data center by three units. The first UPS unit (UPS #1) is located in the data center computer room. Its output at one moment of making measurement was 9,4kW in total. There two more UPS units (UPS #2 and UPS #3) serve the data center, but are located in another room. Their outputs at the same moment were 15,2kW and 11,9kW respectively. So the total out-

put of all three UPS units at that time was 36,5kW. The electricity consumption of the computer room is about 70000-80000 kWh/ month.

The HVAC system is performed by two computer room air conditioner (CRAC) units and its study is represented wider in next chapter. The gaseous firefighting system is performed by three cylinders of fire extinguishing gas (clean agent FS 49).

IT equipment is represented by following parts: two areas with low rate heat emission equipment and area in the middle of the room with computing equipment. The second part created the biggest interest for investigation. The equipment is placed on metal racks with following dimensions: length 0,8m, width 0,8m and height 2,0m. Only one line of racks is established in the room, so from one side of the line a corridor with only equipment inlets is located - so called cold aisle ("equipment inlet side" further in the text). From another side of the line a corridor with only equipment outlets is located – hot aisle ("equipment outlet side" further in the text). The equipment is unevenly stacked within the line of the racks. Openings in raised floor are established under most of the racks in order to provide cool air directly to the equipment. Also some of the equipment have their own fans.

4.2 Description of HVAC-systems

The cooling system of computer room of the data center is performed by two computer room air conditioner (CRAC) units, which are located on perimeter of the room. The CRAC #1 was an original cooling system made by the data center design. It is an air conditioner that consists of a filter, a fan and a cooling unit like it is shown on Figure 18. The nominal cooling capacity is 579kW and the nominal air flow rate is $3,75\text{m}^3/\text{s}$. The cooling liquid is chilled water, which is produced in a cooling unit located elsewhere in the building and distributed to the case study room by insulated chilled water pipes. The temperature of the chilled water is $6...12^\circ\text{C}$ in general.

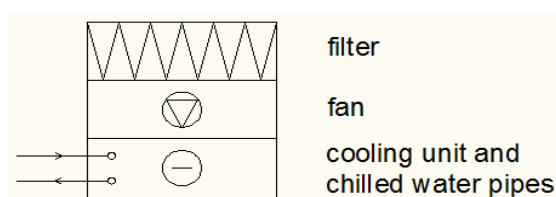


FIGURE 18. Components of CRAC #1

After few years of functioning, the quantity of IT equipment increased together with heat emissions in the data center, so the second cooling unit appeared. The CRAC #2 is cooling unit of an air cooled chiller. The components of the chiller are shown on Figure 19. The liquid in the unit is cooled by means of two-phase vapor compression cycle. Unfortunately, it wasn't possible to obtain exact data about nominal capacity and nominal air flow rate of the CRAC#2.

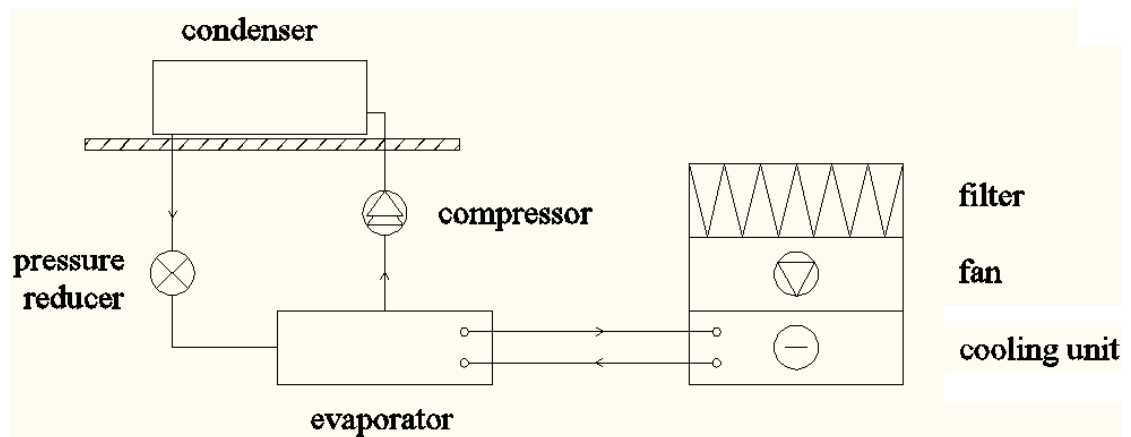


FIGURE 19. Components of the chiller

Work energy is required for functioning of two-phase vapor compression cycle. The liquid in an evaporator takes heat from inside surroundings, becomes gas and transports the heat to a condenser. In the condenser, the gas gives the heat to another surrounding and becomes liquid again. A compressor in the cycle raises pressure of gas to help it with condensing, and a pressure reducer decreases pressure of liquid to help it with evaporation. /16, p.288-289./ In the case study building the condenser was located on the roof of the building, so the heat was released to outside air. It was an air cooled condenser, which in general consists of finned tubes and a fan. The fan forces air to go through condenser coil and release it from heat. /16, p.298-299./

Besides primary operation setting, free cooling could be applied in order to archive energy savings. The principle of free cooling is to use cool outside conditions instead of compressor for cooling. It can be air side and water side. Air side free cooling is mostly based on mixing processes of hot inside and cool outside air. In liquid side free cooling heat exchange happens by means of liquid which is circulating between outside and inside of a building. Liquid-side free cooling can be applied only when outside temperature is lower then the needed temperature of the liquid. In the case study data center, liquid side cooling is applied.

Unfortunately it wasn't possible to calculate heat load prediction of the data center and compare it with capacities of cooling units. The prediction was supposed to be done according to relations showed on Figure 5 in chapter 3.4 Studying HVAC-systems, but total IT power and power system rating values were not available. One more limitation of study is that the temperature of the chilled water of the CRAC units was not recorded during the sampling period.

The temperature set point for both CRAC units was 20,5°C but the temperature sensors were located in the inlet air flow of the units. The units supply IT equipment with cooled air using space under the raised floor as aisle to the equipment. The warm air is gathered on the top of CRAC units, where CRAC inlets are located. The HVAC designer chose contained supply and flooded return as air distribution methods. More about these methods was written in chapter 3.4.1 Air distribution.

4.3 Measurement setup

The measurements were done in November 2012. The measuring period was 6 days (144 hours) starting from 14:15 on 15 of November until 14:00 on 21 of November. Measuring instruments were recording values once in fifteen minutes. Such a long period of measurement and such a short time between measurements were chosen in order to eliminate inaccuracies related to temporary peak loads, presence of personnel in the room and to get a reliable result. Totally, 576 values per each studied property were taken.

The measurements were done using sixteen instruments called Data Loggers Series EBI 20-TH which have accuracy $\pm 0,5^{\circ}\text{C}$ for temperature measurements and $\pm 3\%$ for relative humidity measurements. According to TIA-942 measurements should be done in following way: "Measurements shall be done at a distance of 1,5 m above the floor level every 3 to 6 m along the center line of the cold aisles and at any location at the air intake of operating equipment." /8, p.29/. But the computer room of the data center is not that big – there is no strongly marked cold aisles. There is only one line of equipment supporting constructions with IT equipment and cool air is distributed directly from under floor openings. So application of these rules was a bit difficult.

Four Data Loggers measured air stream in CRAC units, one Data Logger measured under the raised floor, six Data Loggers did it on the inlets of IT equipment and five – on their outlets. The location of each Data Logger is written in the Table 2, and on Figures 20 and 21 is possible to see location of loggers in the room from top and back view.

TABLE 2. Location of the Data Loggers in the room

Number of a Logger	Height above the raised floor	Location in room
CRAC units		
1	–	inlet of CRAC unit #1
2	–	inlet of CRAC unit #2
3	–	outlet of CRAC unit #1
4	–	outlet of CRAC unit #2
Under the raised floor		
5	-0,25 m	In the middle of the rack line under IT equipment
Equipment inlet side of racks (2,4 meters distance between loggers in horizon)		
6	1,5 m	On supporting construction
7	1,5 m	On supporting construction
8	1,5 m	On supporting construction
9	0,7 m	On supporting construction, under #6
10	0,7 m	On supporting construction, under #7
11	0,7 m	On supporting construction, under #8
Equipment outlet side of racks (1,6 meters distance between loggers in horizon)		
12	1,5 m	On supporting construction
13	1,5 m	On supporting construction
14	1,5 m	On supporting construction
15	1,5 m	On supporting construction
16	1,5 m	On supporting construction

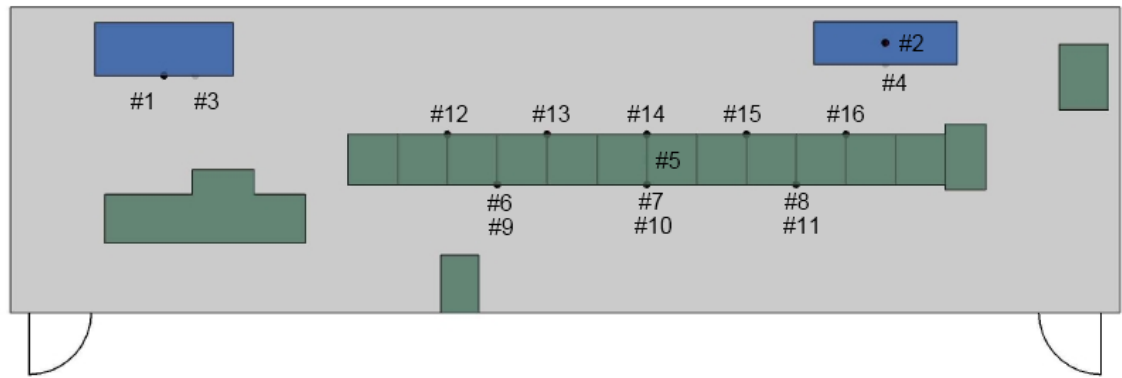


FIGURE 20. Top view of case study room of the data center

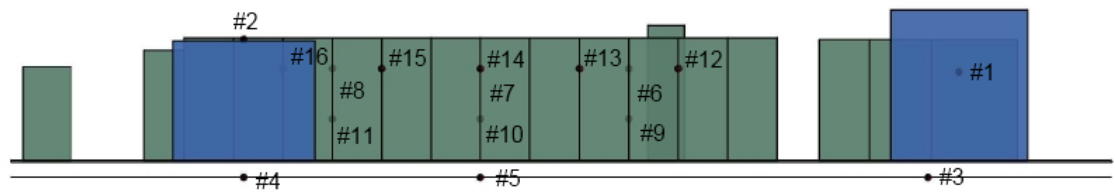


FIGURE 21. Back view of case study room of the data center

4.4 Measurement results and analysis of results

After measurements were done, the Data Loggers were removed from the data center and processing work of obtained data began. Before making any discussion and conclusion, it should be noticed that the obtained data has some limitations. They are: inaccuracy of measuring devices, not exactly representative locations for measuring air characteristics and some other possible disturbances (presence/absence of operating personal, maintain/repair works, etc.). Also the presence of own fans inside some IT equipment makes it difficult to analyze the distribution of air temperatures at different location in racks.

4.4.1 Average and critical values

Every Data Logger did 576 measurements of temperature and 576 measurements of relative humidity that is why first accomplished analysis was to calculate average value of all measurements and to find out minimal and maximum values in those measurements. In Table 3 it is possible to see average value of temperature and relative humidity of six days period per each logger, and also the biggest and the lowest value of measured air properties during the period of measurements.

TABLE 3. Average and critical values of temperature and relative humidity

Data Logger	$t_{av}, ^\circ\text{C}$	$t_{max}, ^\circ\text{C}$	$t_{min}, ^\circ\text{C}$	$RH_{av}, \%$	$RH_{max}, \%$	$RH_{min}, \%$
1	26,2	26,8	25,7	27,0	30,0	23,9
2	23,6	24,3	22,6	31,3	35,4	27,0
3	23,2	23,8	22,7	31,6	34,8	28,0
4	14,6	16,7	11,2	54,0	69,1	42,0
5	22,7	23,1	22,3	33,4	36,4	29,6
6	23,6	24,2	23,1	31,6	34,4	28,5
7	24,5	25,1	23,8	30,4	33,4	26,4
8	16,6	21,8	14,2	47,1	57,5	37,9
9	23,4	24,1	23,0	31,6	34,7	28,0
10	23,5	24,1	22,6	31,8	34,9	27,9
11	15,5	20,6	12,5	51	64,2	39,2
12	25,9	26,9	24,0	27,9	34,4	24,4
13	23,9	24,5	23,3	31,8	35,1	27,9
14	23,2	24,2	22,6	33,0	36,2	29,2
15	21,7	24,7	20,7	36,9	43,8	31,6
16	18,3	24,2	16,2	45,2	54,0	34,0

A brief look at the column with average temperatures shows some interesting things, e.g. for Data Logger #2 it is 23,6°C and for Data Logger #3 it is 23,2°C. They are almost equal although location #2 is inlet of CRAC unit #2 and location #3 is outlet of CRAC unit #1. Data Loggers #8 and #11 were located at same supporting construction with difference of 0,8m in height. As it was expected temperature in location #8 is bigger than in location #11, but they both have a quite big temperature difference from other Data Loggers that measured inlet temperatures of IT equipment. Data Loggers #12, #13, #14, #15 and #16 measured outlet temperatures from IT equipment and their values are constantly rising starting from location #16 to location #12.

4.4.2 CRAC units

The locations responsible for CRAC units research were #1, #2, #3 and #4 and the location #5 was responsible for research of air mix from the two CRAC units. The average values for six days period of measurements were calculated, and a simple

picture of the processes carrying out in CRAC units according to them is represented on Figure 22. Here the process 1-3 represents CRAC#1, and the process 2-4 represents CRAC#2.

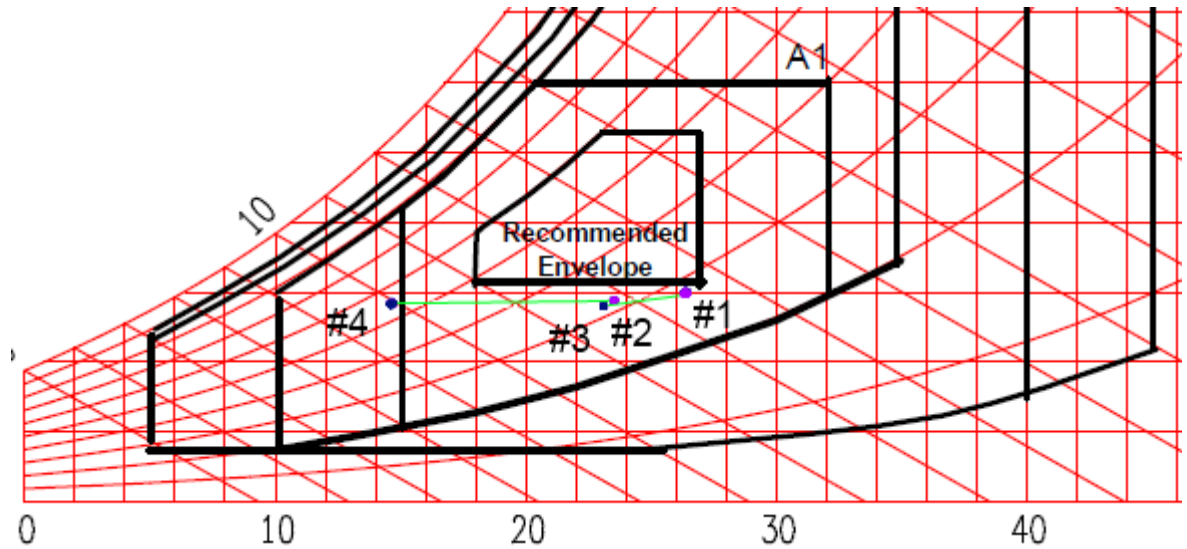


FIGURE 22. Cooling processes of the CRAC units

It is easy to see that air properties of location #2 and #3 are very similar to each other, although in theory location #1 and #2 should be quite similar as they are inlets of CRAC units located in the same room. This difference in theory and practice shows the importance of correct air distribution in a room. The CRAC#1 is located farther from the studying equipment than CRAC#2 so it's more complicated to take the heat out of equipment, and also low rate emission equipment influences a bit to the temperature raise of hot exhaust air (location #1).

In order to check if the cooling system removes moisture from air, the values of absolute humidity were retrieved from values of dry bulb temperature and relative humidity by means of Mollier's chart. For the location #1 it is 5,69g/kg, for location #2 it is 5,65g/kg, for location #3 it is 5,57g/kg and for location #4 it is 5,56g/kg. It was expected that absolute humidity difference would be less at inlets and more at outlets. The following comparisons in absolute humidity values were done:

1. Comparison of CRAC inlets

CRAC#1: 5,69g/kg

CRAC#2: 5,65g/kg,

so $\Delta X_{\text{INLET}} = X_1 - X_2 = 5,69 - 5,65 = 0,04 \text{ g/kg}$

2. Comparison of CRAC outlets

CRAC#1: 5,57g/kg

CRAC#2: 5,56g/kg,

so $\Delta X_{\text{OUTLET}} = X_3 - X_4 = 5,57 - 5,56 = 0,01 \text{ g/kg}$

3. Comparison between the cooling processes.

CRAC#1: 5,69g/kg and 5,57g/kg CRAC#2: 5,65g/kg and 5,56g/kg

so $\Delta X_{\text{CRAC1}} = X_1 - X_3 = 5,69 - 5,57 = 0,12 \text{g/kg}$

so $\Delta X_{\text{CRAC2}} = X_2 - X_4 = 5,65 - 5,56 = 0,09 \text{g/kg}$

After the calculation it is seen that absolute humidity difference is less at outlets and more at inlets, but all the differences in comparisons are quite small and hardly distinguished on Mollier's chart, so they can be ignored. So the cooling system doesn't really remove moisture from air, it stays almost constant.

One more analysis of average values was done. But in this case it was calculating of on average values for few days at the same time. For example, at location #1, at 15:15 on 15 of November the value of temperature was 25,8°C. At 15:15 on 16 of November at the same place the value was 26,0°C. On 17 of November it was 26,1°C, on 18 of November it was 26,2°C, on 19 of November it was 26,3°C and on 20 of November it was 26,3°C. So the average temperature in location #1 at 15:15 was 26,1°C. The same process was applied for each value during 24 hours. The obtained data is represented on Figures 23-27.

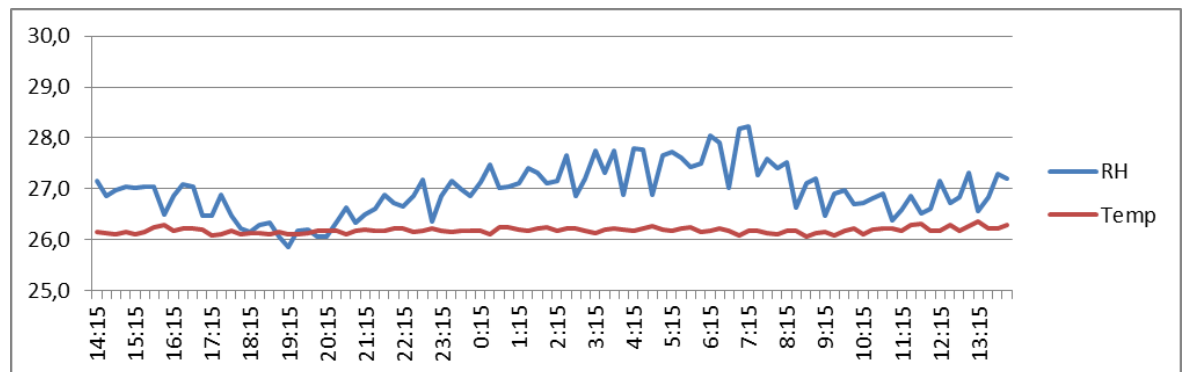


FIGURE 23. Average day at location #1

On Figure 23 both temperature and relative humidity can be considered as constant during all the day (the small changes can be ignored as the accuracy of device is $\pm 0,5^\circ\text{C}$ for temperature and $\pm 3\%$ for relative humidity measurements, and in location #1 the change is less).

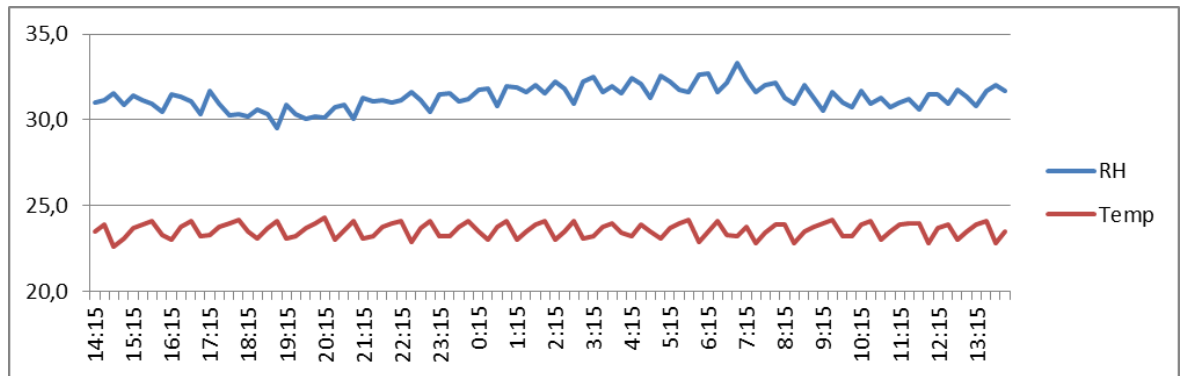


FIGURE 24. Average day at location #2

On Figure 24 both temperature and humidity can't be considered as constant during the day, because the changes exceed the accuracy of devices and are about 5% of relative humidity and 1,5°C for temperature. To make any conclusions, the location #2 will be considered wider in chapter 4.4.6 Variation in time.

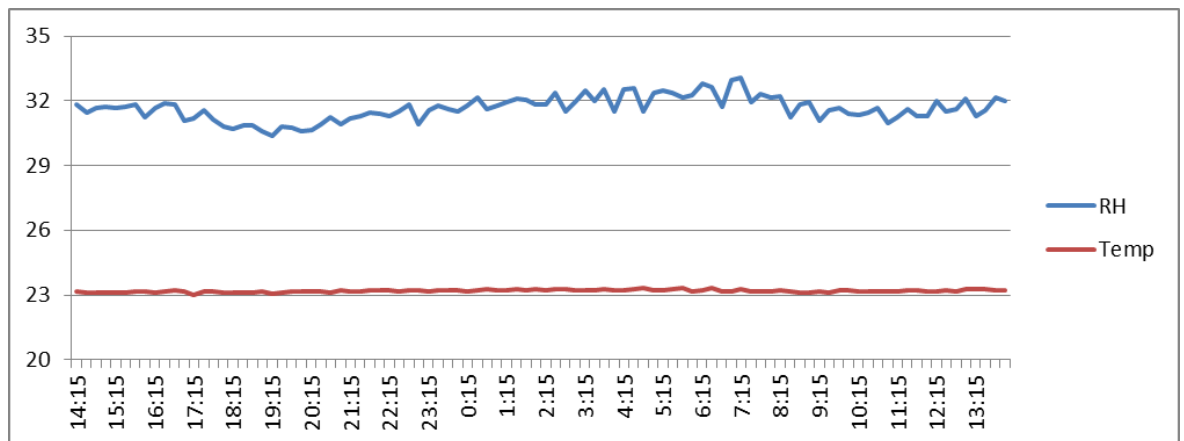


FIGURE 25. Average day at location #3

On Figure 25 both temperature and relative humidity can be considered as constant during all the day (change is less is than $\pm 0,5^{\circ}\text{C}$ for temperature and $\pm 3\%$ for relative humidity).

On Figure 26 both temperature and humidity can't be considered as constant during the day, because the changes exceed the accuracy of devices and are about 13% of relative humidity and 8°C for temperature. To make any conclusions, the location #4 will be considered wider in chapter 4.4.6 Variation in time.

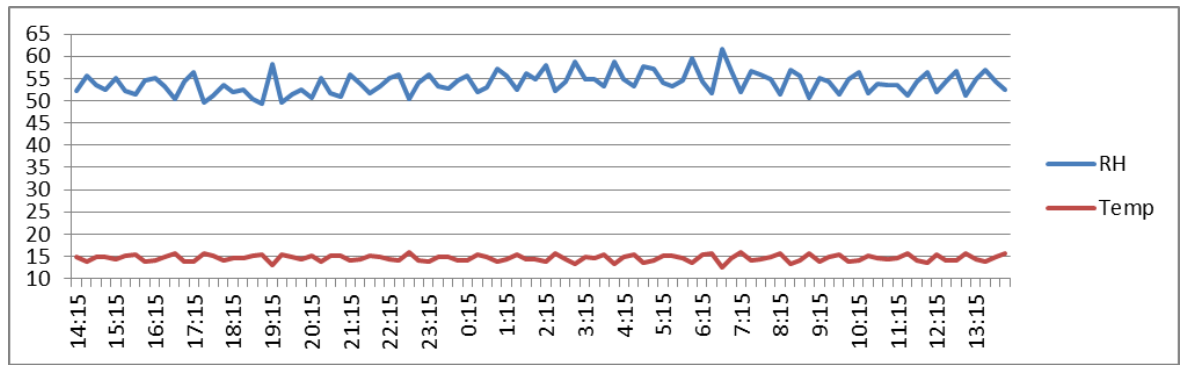


FIGURE 26. Average day at location #4

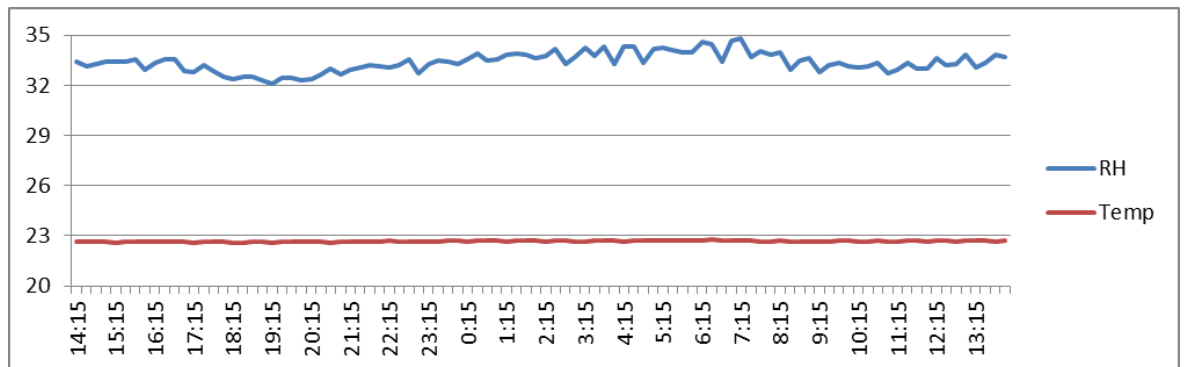


FIGURE 27. Average day at location #5

On Figure 27 both temperature and relative humidity can be considered as constant during all the day (change is less than $\pm 0,5^{\circ}\text{C}$ for temperature and $\pm 3\%$ for relative humidity).

The location #5 is a place of interest for research because it is located under the raised floor and in the middle of the line with IT equipment. To see the power of mixing of air from CRAC units and degree of influence of each the process was drawn according to average values of all the period of measurements on Mollier's chart. The process is represented on Figure 28.

According to theoretical laws the mixing point must be on a line that joins the points with characterize the two mixing mediums. The law was followed in any moment of the measurements, but on Figure 28 the values are average, so there is a small deviation.

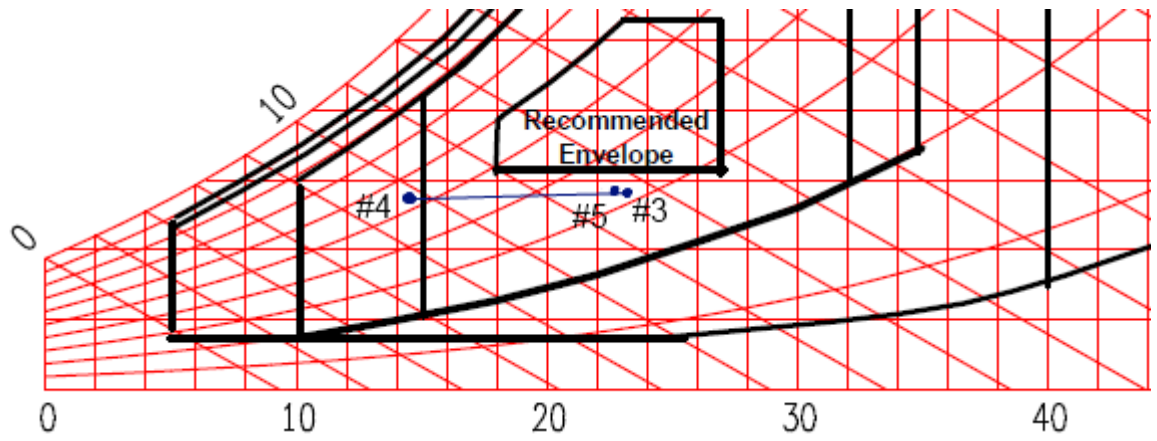


FIGURE 28. Mixing process under the raised floor

The approximate degree of influence of CRAC units on air properties in set point #5 can be expressed in ratio of volume flows from each CRAC unit that reach the point and mix there. The volume flow q_1 of CRAC unit #1 refers to the volume flow q_2 of CRAC unit #2 as $\frac{q_1}{q_2} = \frac{\Delta t_{5-4}}{\Delta t_{3-5}} = \frac{22,7 - 14,6}{23,2 - 22,7} = 16,2$. So according to the obtained values influence of the CRAC unit #1 is about sixteen times bigger than of CRAC unit #2.

To have an approximate picture of characteristics of air that passes through this location, maximum possible area of changes was build according to minimum and maximum values of dry bulb temperature and relative humidity during all the measuring period on Molliers's chart. This area is represented on Figure 29 as a purple pattern. The green point on the pattern represents average value of temperature and relative humidity for all the measuring period.

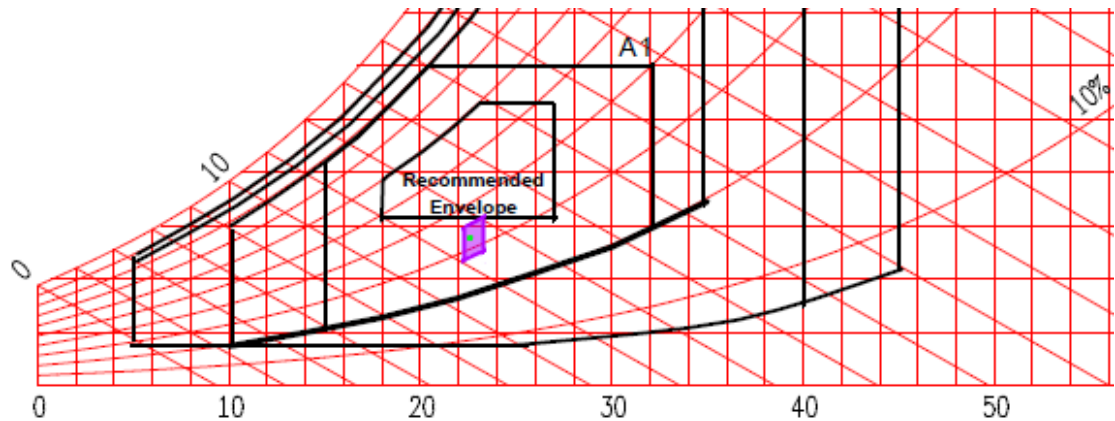


FIGURE 29. Data Logger #5 values on Mollier's chart

Almost at the all period of time the indoor air characteristics at the set point corresponded to allowable envelope A1 according to ASRAE thermal guidelines 2011, and the air characteristics were quite close to recommended envelope boundaries.

4.4.3 Equipment inlets

The locations #6, #7, #8, #9, #10 and #11 were responsible for research of IT equipment inlets air characteristics. To have an approximate picture of characteristics of air that passes through these locations, maximum possible areas of changes were build according to minimum and maximum values of dry bulb temperature and relative humidity during all the measuring period on Mollier's chart. These areas are represented on Figure 30 and 31 as purple patterns. The green points on patterns represent average values of temperature and relative humidity for all the measuring period.

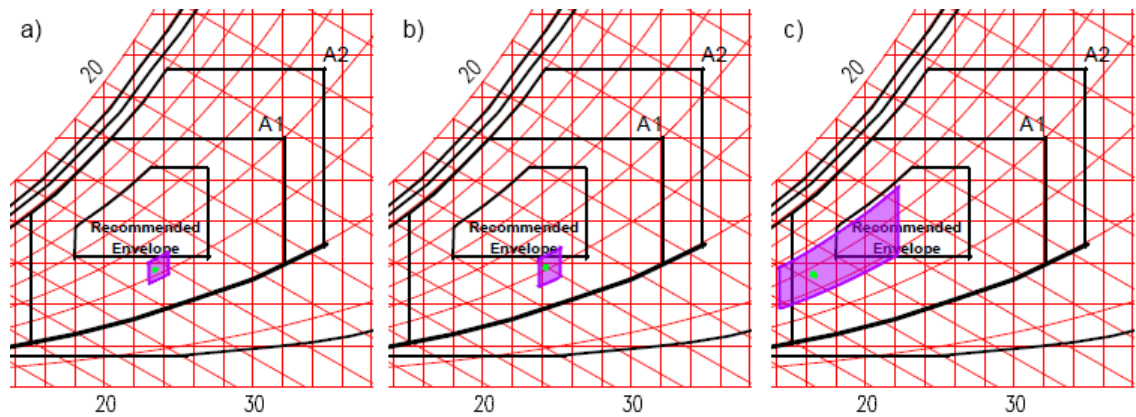


FIGURE 30. Data Logger #6, #7, #8 values are a, b, c on Mollier's chart respectively

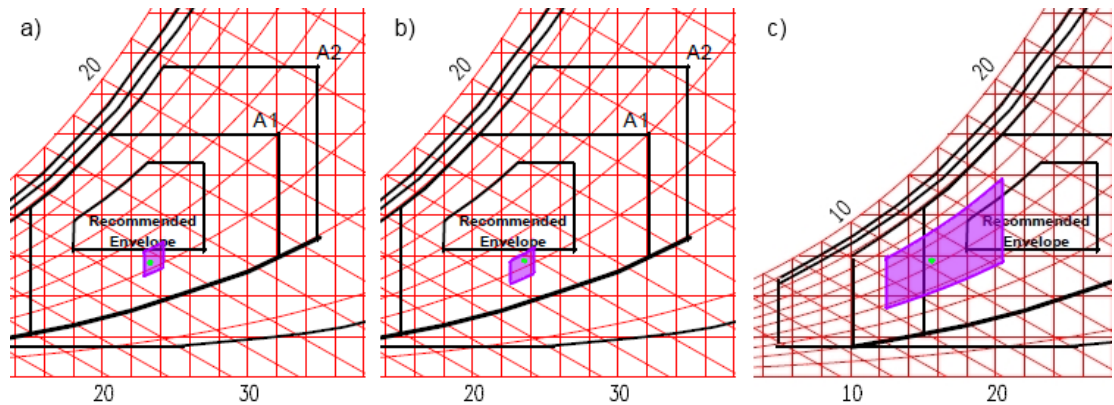


FIGURE 31. Data Logger #9, #10, #11 values are a, b, c on Mollier's chart respectively

It is seen from the charts that air properties in locations #6, #7, #9 and #10 correspond to A1 class according to ASHRAE classification, and the average values are close to be even in recommended envelope and could be in it if the air contained a bit more moisture. The air properties of locations #8 and #11 correspond to A2 class of the classification mostly because of too cool temperatures. This is because the locations are too close to CRAC unit #2.

4.4.4 Equipment outlets

The set points #12, #13, #14, #15 and #16 were responsible for research of IT equipment outlets air characteristics. These measurements were done to see the overall picture of air characteristics change. For this maximum possible areas of changes were build according to minimum and maximum values of dry bulb temperature and relative humidity during all the measuring period on Molliers's chart. These areas are represented on Figure 32 as purple patterns. The green points on patterns represent average values of temperature and relative humidity for all the measuring period.

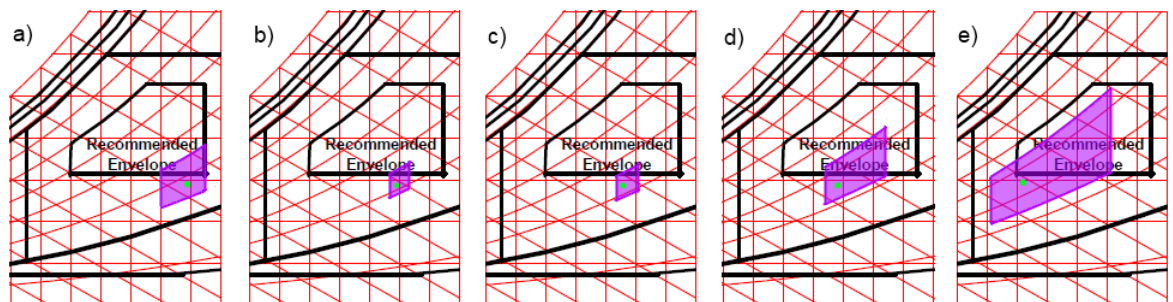


FIGURE 32. Data Logger #12, #13, #14, #15, #16 values a, b, c, d, e on Mollier's chart respectively

If to follow from picture **a** to picture **e**, the values of temperature are constantly reducing. This reduce goes from equipment located closer to CRAC #1 to equipment located closer to CRAC #2. It might be explained by difference is supply temperatures of the units (23,6°C and 14,6°C).

4.4.5 Variations in space

To have the overall picture of temperature and relative humidity distribution in the studying room, the average values from Table 3 were put on the AutoCAD 3D model and are represented on Figures 33-35.

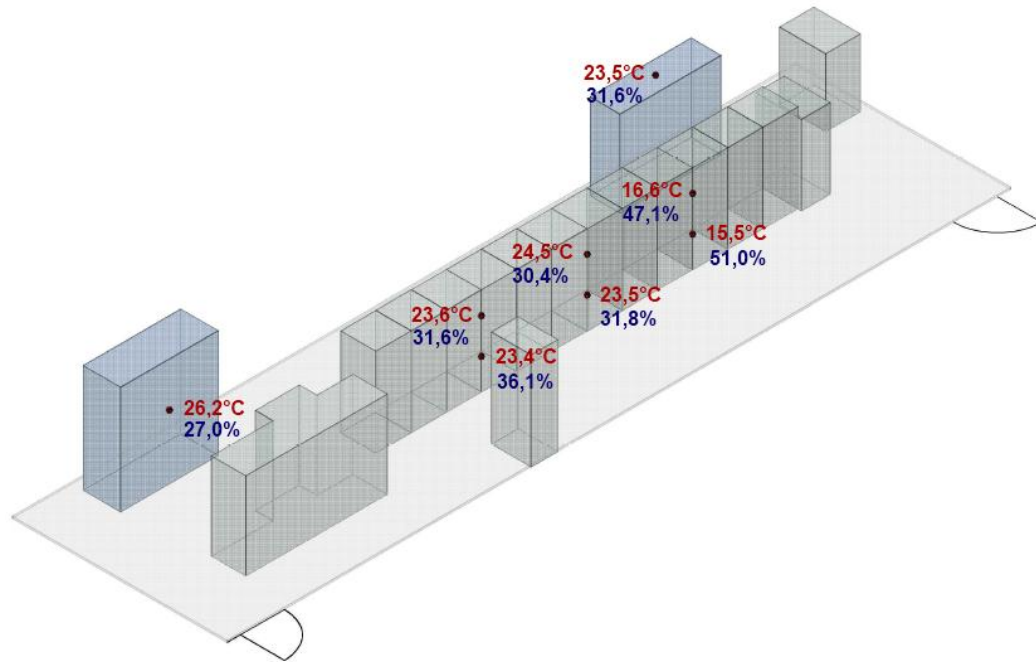


FIGURE 33. Average temperature and relative humidity values in space, front view

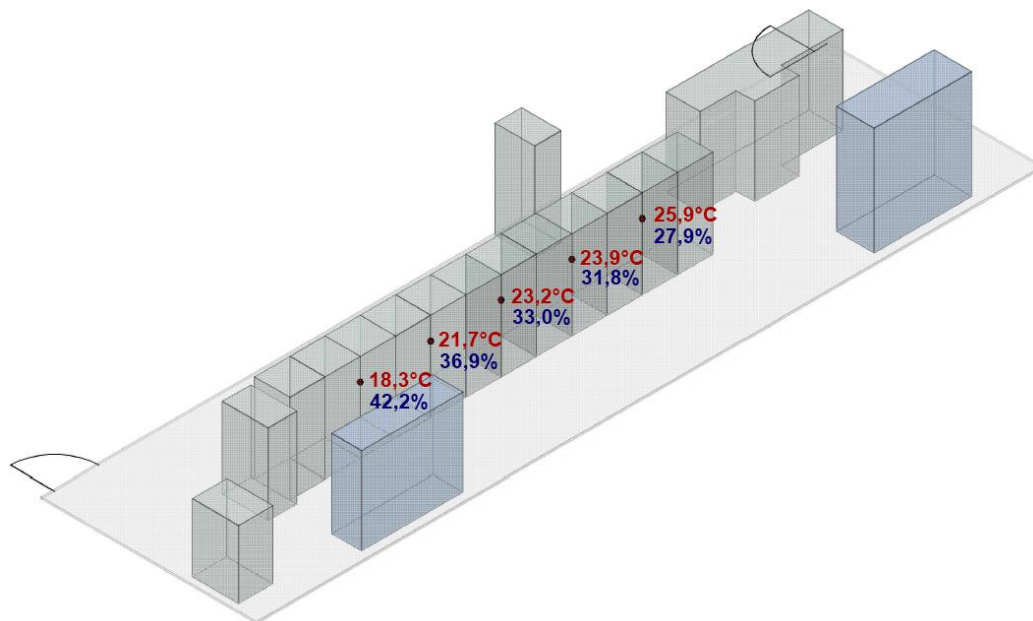


FIGURE 34. Average temperature and relative humidity values in space, back view

The five measurements on locations #12-16 were done to have the overall picture of temperature changes of air which goes through IT equipment. The average values of temperature distribution on height 1,5m are shown on Figure 35.

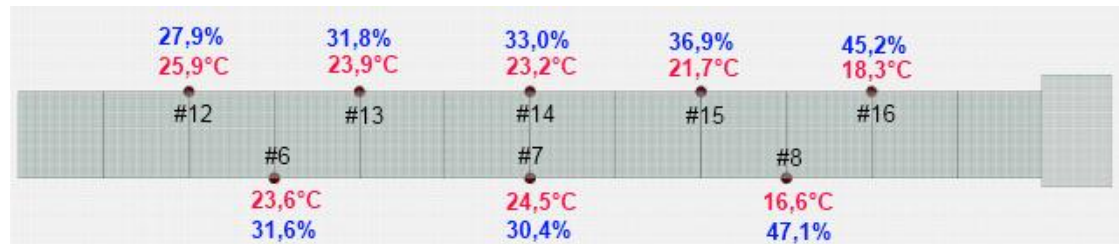


FIGURE 35. Average temperature and relative humidity values in space, top view

The upper part of the Figure 35 represents properties of exhaust air and lower part represents properties of inlet air. There is a contradiction in the average values on location #7, where the inlet temperature is higher then outlet one, which can be caused by the close location to IT then in every other place, it could influence on obtained data.

4.4.6 Variation in time

Interesting variation in values of temperature happened in CRAC#2 at location 2 and 4. The results of all the period of measurements are presented on diagrams in appendices 7 and 9, and also in table form on Tables 4 and 5.

From Table 4 it is seen that the biggest variation in temperature and relative humidity values is during the first day of measurements. Also the temperature variation is big for the last day and the humidity one - for forth day. Daily average temperature values stayed almost constant and Daily average relative humidity values increased a bit on third and forth day, but in general didn't change much.

TABLE 4. Location #2 values

Number of day	Maximum		Minimum		Average		Variation	
	RH, %	T, °C	RH, %	T, °C	RH, %	T, °C	Δ RH	Δ T
1	34,7	24,3	27,0	22,6	30,8	23,6	7,7	1,7
2	33,4	24,2	27,0	22,8	29,9	23,6	6,4	1,4
3	35,2	24,2	30,8	22,8	32,8	23,6	4,4	1,4
4	35,4	24,3	27,9	22,8	32,7	23,6	7,5	1,5
5	34,2	24,2	28,3	22,7	30,9	23,5	5,9	1,5
6	34,1	24,3	28,1	22,7	30,8	23,5	6,0	1,6
Average	34,5	24,3	28,2	22,7	31,3	23,6	6,3	1,5

TABLE 5. Location #4 values

Number of day	Maximum		Minimum		Average		Variation	
	RH, %	T, °C	RH, %	T, °C	RH, %	T, °C	Δ RH	Δ T
1	67,3	16,6	43,1	11,6	51,7	14,9	24,2	5,0
2	65,5	16,6	42,0	11,8	50,7	14,9	23,5	4,8
3	67	16,7	49,2	11,8	55,7	14,9	17,8	4,9
4	69,1	16,7	45,0	11,9	55,9	14,8	24,1	4,8
5	68,4	16,4	46,4	11,2	55,4	14,0	22,0	5,2
6	68,6	16,5	45,2	11,2	54,7	14,2	23,4	5,3
Average	67,7	16,6	45,2	11,6	54,0	14,6	22,5	5,0

From Table 5 it is seen that the biggest variation in temperature values is during the last day, and the biggest variation in relative humidity values is during the first day. Also the temperature variation is big for the fifth day and the humidity one - for fourth day. It is interesting that daily average temperature values stayed almost constant during four days and then suddenly dropped for 0,8°C. And daily average relative humidity values suddenly increased for 5% after the second day.

In Table 5 the values of temperature variation for days five and six are bigger than allowed maximum rate of change by ASHRAE 2011 Thermal guidelines [6], which is 5°C/hr for data centers employing tape drives. To see if the case study data center meets the guidelines, the values of the fifth and the sixth days at location #4 were

studied more precisely. The diagrams with all the measured values during those days are represented in Appendix 9 on Figures 5 and 6. In order to have precise number of the change in values during an hour, tables with maximum and minimum temperature values and the difference between them was calculated per each possible hour. The tables are represented in Appendix 22 and 23. In the tables, the values marked with yellow colour correspond to values between 4,5 and 4,9°C/hr. the values marked with red colour correspond to the critical value of 5°C/hr and above. For the fifth day of measurements, twenty one values of temperature change from ninety two possible ones (22,8%) were above 4,5°C/hr and three of them were 5°C/hr (3,3%). No values above 5°C/hr were detected. For the sixth day of measurements, thirty eight values of temperature change from ninety two possible ones (41,3%) were above 4,5°C/hr and three of them were 5°C/hr (3,3%). No values above 5°C/hr were detected. So the case study data center corresponds to A1-A4 class according to ASHRAE.

5 DISCUSSION AND CONCLUSION

In conclusion I want to summarize that thermal climate does have influence on functioning of computing devices, and it's very important to maintain air properties in proper range for efficient and reliable work. Out of the range the equipment can even switch off or be damaged. Increased ambient temperature could increase needed server power by increase in fan power consumption. Also it could influence on performance degradation, increased acoustic noise and increased server costs (the poorer thermal parameters are, the more expensive high-temperature-rated components are needed). Moisture level influences on dielectric properties. Its excess could cause loss of adhesive strength in dielectric layers and corrosion in places of condensation, and its lack could increase possibility of electrostatic discharge effect.

To determine this proper range there are some organizations that permanently make tests and researches to restrict or to ease the range, like ASHRAE TC 9.9 which made already two updates of their data center standard. According to the latest thermal guidelines, there are four classes of data center in the classification that correspond to set ranges of air properties: A1, A2, A3 and A4. The difference between the classes is in tightness of environmental control. The bigger the number of the class is, the wider the temperature and moisture range is accepted.

Nowadays a big question in the thermal climate of a data center is about necessity of humidification. In theory its purpose is to increase data center reliability, but on practice quite often humidifiers create more problems than profit. They increase investment and operational costs, but can function not in proper way (depending on quality and monitoring property of a sensor). Also humidification was excluded as primary control for preventing electrostatic discharge effects by Electrostatic Discharge Association as it has no beneficial effect at low voltage (threshold levels for electrostatic discharge damage are less than 100V).

After the needed range of air properties is chosen, important features to think about are the means of achieving this range. One of them is air distribution. Well done air distribution system can significantly reduce engineering requirements. The main aim is to separate exhaust air of equipment from supply air of equipment to prevent overheating. Airflows are constrained only by room constructions, so efficiency of the system depends on quality of their separation. There are few principal ways to distribute air depending on environmental requirements and performance of a data center.

The other mean of achieving the needed range of air properties is cooling system itself. Cooling proceeds by heat exchange between warm indoor air and another cool fluid. There are few basic heat removal methods, which are different in type and number of fluids that remove heat. The fluid can be water, glycol, refrigerant and air. Some of the methods use up to three cycles with different fluids inside for cooling. Each method has its own advantages, disadvantages and range of application.

The practical part of the thesis was investigation of a five year old functioning computer room of a data center. Air distribution and cooling systems were studied, and measurements of temperature and relative humidity were done in November 2012. Analysis of the measured values showed following features. First of all, the computer room had quite good air properties. At locations #6, #7, #9 and #10 part of measured values corresponded to recommended envelope, and part of them – to A1 class. At locations #8 and #11 patterns that represent the maximum area of change of measured values on Mollier's chart were about eight times bigger than at locations #6, #7, #9 and #10. A part of measured values corresponded to A1 class and the other part to A2 class. So the computer room can be considered as A2 class according to ASHRAE classification (the A2 class corresponds to data centers with volume servers, storage

products, personal computers and workstations with some environmental control). The locations #8 and #11 could be offered for further investigation to see if the temperature there is still lower than at other inlet locations and if it is then solve this problem in order to have the data center corresponding A1 class.

The temperature spreading in the room is so that the temperature gradient goes from CRAC#2 to CRAC#1 along the room, from equipment inlet side to equipment outlet side on the width of the room, and from down to up on the height of the room. But in location #7 the direction of temperature gradient is reverse - from equipment outlet side to inlet side. I assume that the measuring instrument was located much closer to IT equipment than in other places (equipment is unevenly stacked within racks), so it could influence on the measured value. The location #7 could be offered for further investigation to see if the temperature there is still higher than at other inlet locations and at outlet location #14 and if it is then to find the reason.

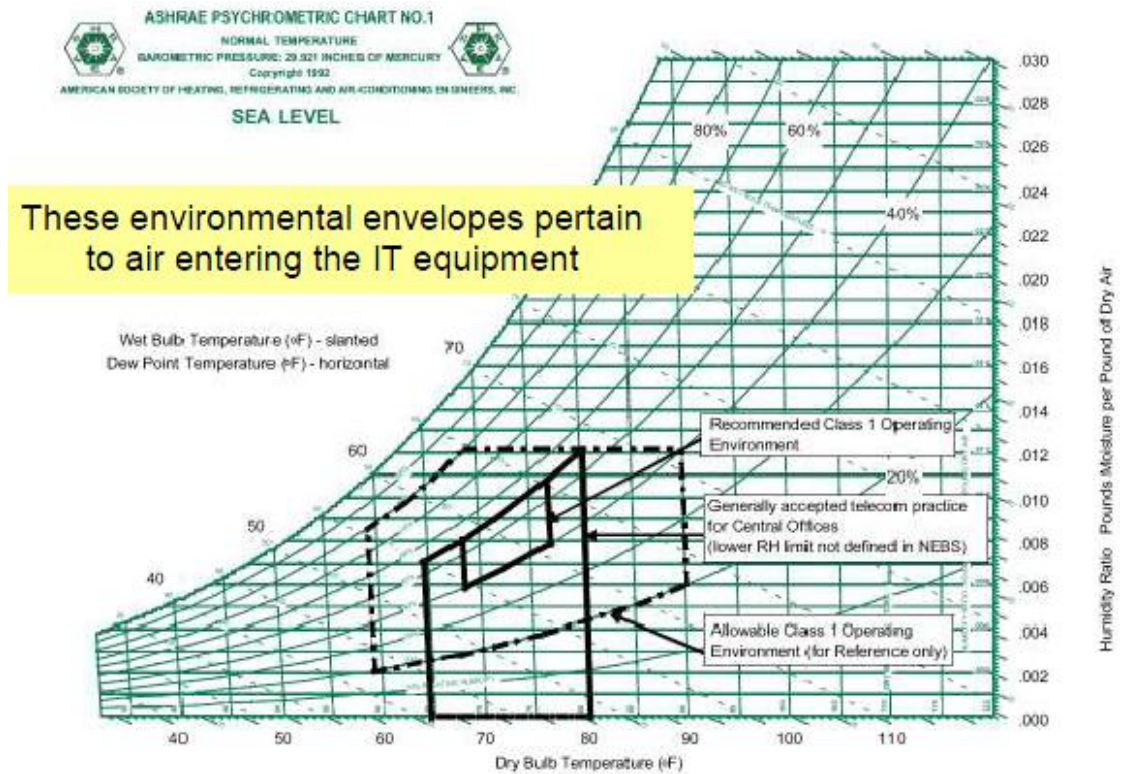
After some calculation, it was found out that in the middle of the line of racks with equipment, under the raised floor, at location #5 the difference between airflows coming from CRAC units is big. At this location the airflow of CRAC#1 is about sixteen times bigger than the airflow of CRAC#2, although the CRAC#1 is located farther from the IT equipment. Also CRAC units have different temperature settings for cooling: for CRAC#1 it is $\Delta t = 3^{\circ}\text{C}$ and for CRAC#2 it is $\Delta t = 9^{\circ}\text{C}$. A decrease in the temperature settings for CRAC#2 might solve the problems at locations #8 and #11. Another calculation showed that both CRAC units almost didn't remove moisture from inside air during the sampling period. The difference in absolute humidity between inlet and outlet air was 0,09...0,12g/kg.

It should be reminded that temperature and relative humidity measurements were not done precisely: the measuring devices were located close to inlets and outlets of IT equipment, but not next to (on supporting device). So the values show overall picture of heat distribution.

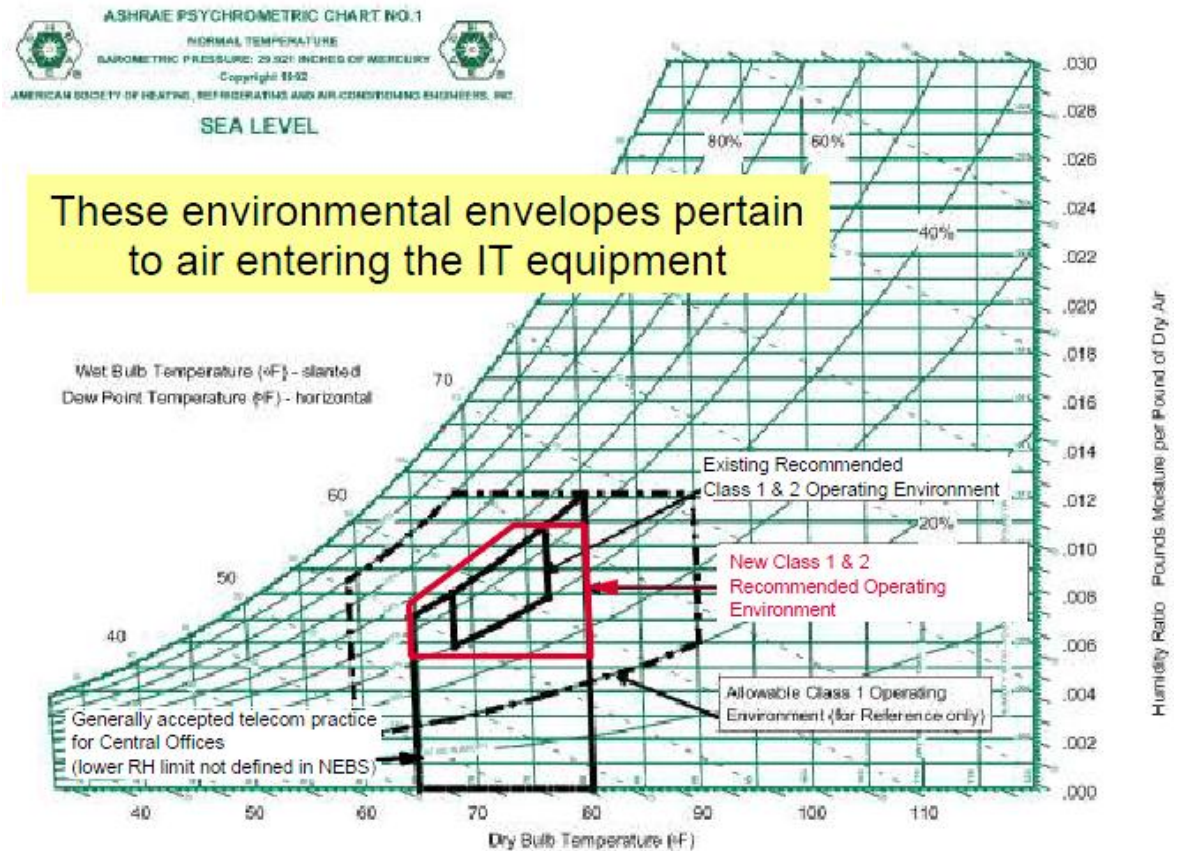
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2004 ASHRAE environmental envelopes for data centers /9, p.1/



2008 ASHRAE new recommended envelope /9, p.3/



APPENDIX 3

Differences between 2004 and 2008 versions of recommended envelopes /9, p.2/

	2004 Version	2008 Version
Low End Temperature	20°C	18°C
High End Temperature	25°C	27°C
Low End Moisture	40% RH	5,5°C Dew Point
High End Moisture	55% RH	60% and 15°C Dew Point

APPENDIX 4

ASHRAE 2008 Thermal guidelines /6, p.4/

class	Equipment environment specifications									
	Product operation a,b							Product power off b,c		
	Dry bulb temperature (°C)		Humidity range, Non condensing		Maximum dew point (°C)	Maximum elevation (m)	Maximum rate of change (°C/h)	Dry bulb temperature (°C)	Relative humidity (%)	Maximum Dew Point (°C)
	Allowable	Recommended	Allowable (% RH)	Recommended						
1	15 to 32 d	18 to 27 e	20 to 80	5,5°C DP to 60% RH and 15°C DP	17	3050	5/20 f	5 to 45	8 to 80	27
2	10 to 35 d	18 to 27 e	20 to 80	5,5°C DP to 60% RH and 15°C DP	21	3050	5/20 f	5 to 45	8 to 80	27
3	5 to 35 d,g	N/A	8 to 80	N/A	28	3050	N/A	5 to 45	8 to 80	29
4	5 to 40 d,g	N/A	8 to 80	N/A	28	3050	N/A	5 to 45	8 to 80	29

a. Product equipment is powered on.

b. Tape products require a stable and more restrictive environment (similar to Class 1). Typical

requirements: minimum temperature is 15°C, maximum temperature is 32°C, minimum relative

humidity is 20%, maximum relative humidity is 80%, maximum dew point is 22°C, rate of change of temperature is less than 5°C/h, rate of change of humidity is less than 5% RH per hour, and no condensation.

c. Product equipment is removed from original shipping container and installed but not in use, e.g., during repair maintenance, or upgrade.

d. Derate maximum allowable dry-bulb temperature 1°C/300 m above 900 m.

e. Derate maximum recommended dry-bulb temperature 1°C/300 m above 1800 m.

f. 5°C/hr for data centers employing tape drives and 20°C/h for data centers employing disk drives.

g. With diskette in the drive, the minimum temperature is 10°C.

2011 and 2008 Thermal Guideline Comparisons /6, p.7/

2011 classes	2008 classes	Applications	IT Equipment	Environmental Control
A1	1	Data center	Enterprise servers, storage products	Tightly controlled
A2	2		Volume servers, storage products, personal computers, workstations	Some control
A3	N/A		Volume servers, storage products, personal computers, workstations	Some control
A4	N/A		Volume servers, storage products, personal computers, workstations	Some control
B	3	Office, home, transportable environment, etc.	Personal computers, workstations, laptops, and printers	Minimal control
C	4	Point-of-sale, industrial, factory, etc.	Point-of-sale equipment, ruggedized controllers, or computer and PDAs	No control

APPENDIX 6(1)

Data Logger #1

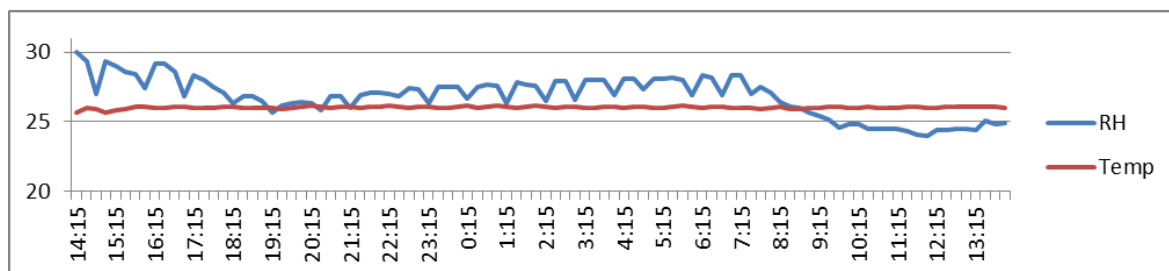


FIGURE 1. Measurements of 15 – 16 of November

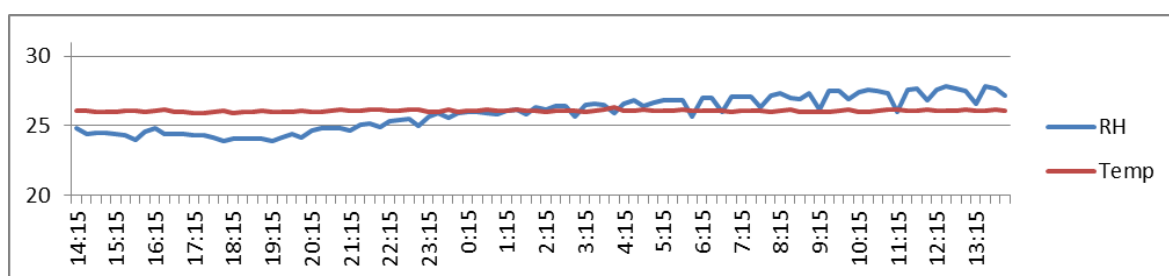


FIGURE 2. Measurements of 16 – 17 of November

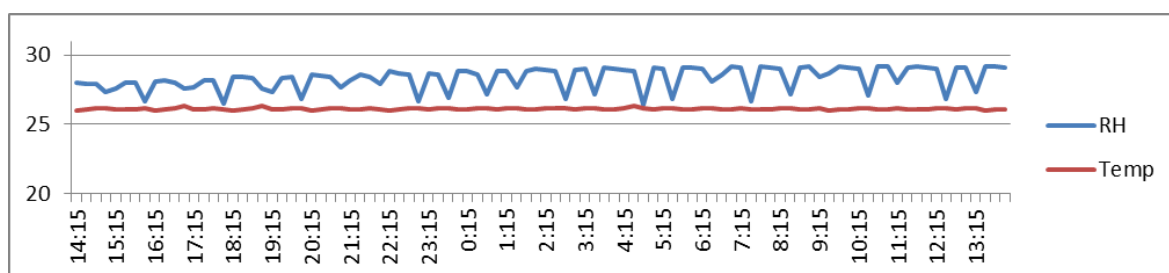


FIGURE 3. Measurements of 17 – 18 of November

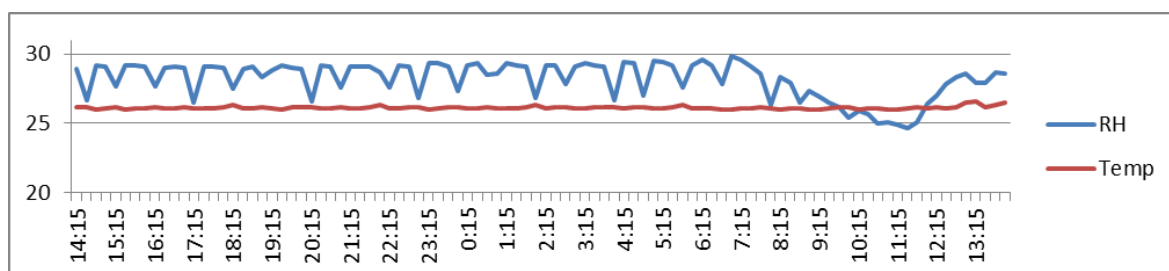


FIGURE 4. Measurements of 18 – 19 of November

APPENDIX 6(2)

Data Logger #1

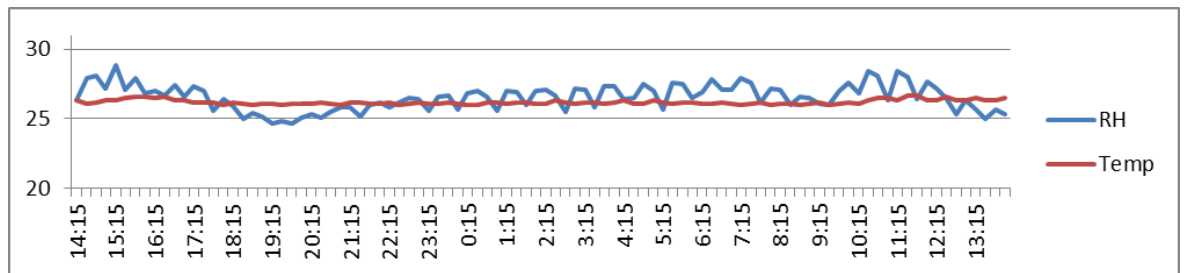


FIGURE 5. Measurements of 19 – 20 of November

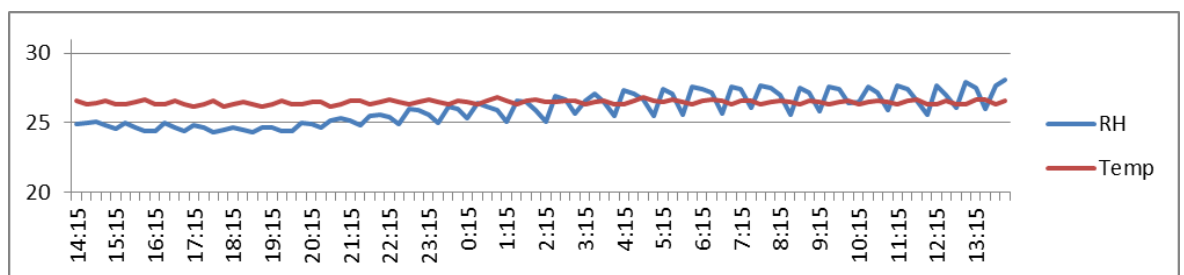


FIGURE 6. Measurements of 20 – 21 of November

APPENDIX 7(1)

Data Logger #2

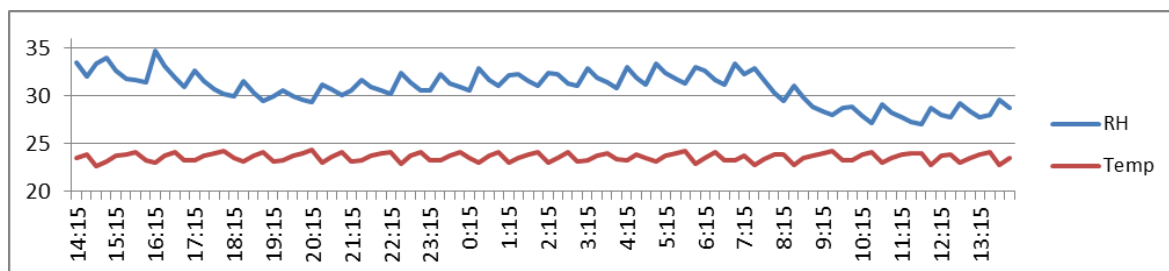


FIGURE 1. Measurements of 15 – 16 of November

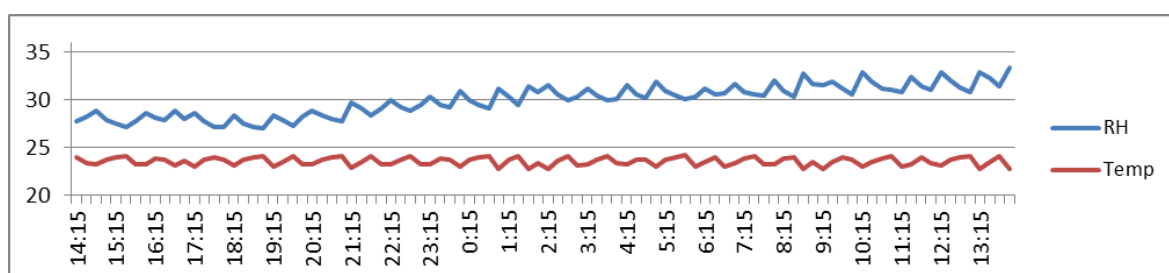


FIGURE 2. Measurements of 16 – 17 of November

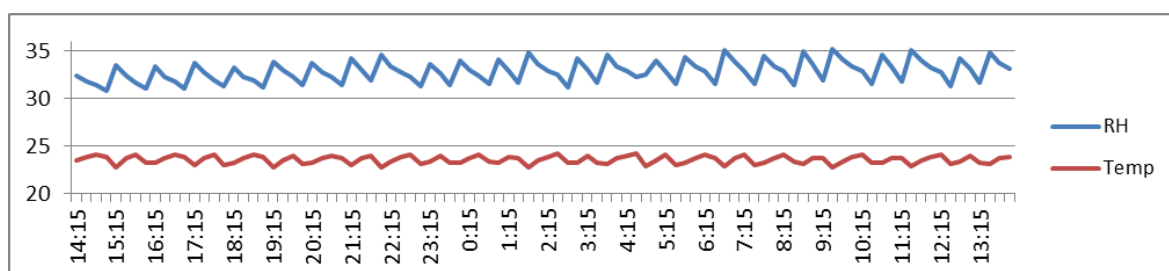


FIGURE 3. Measurements of 17 – 18 of November

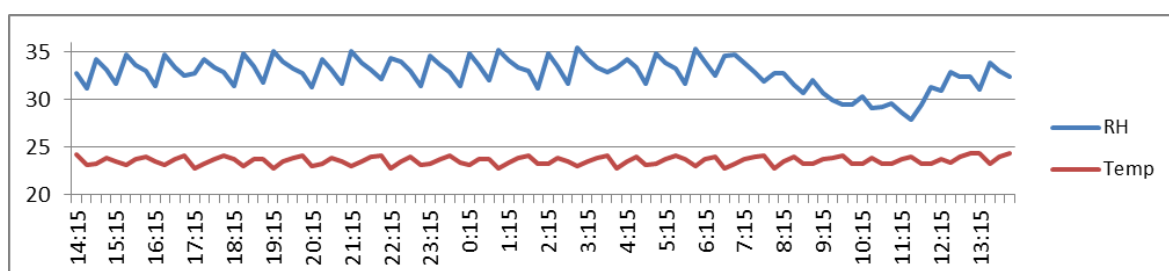


FIGURE 4. Measurements of 18 – 19 of November

APPENDIX 7(2)

Data Logger #2

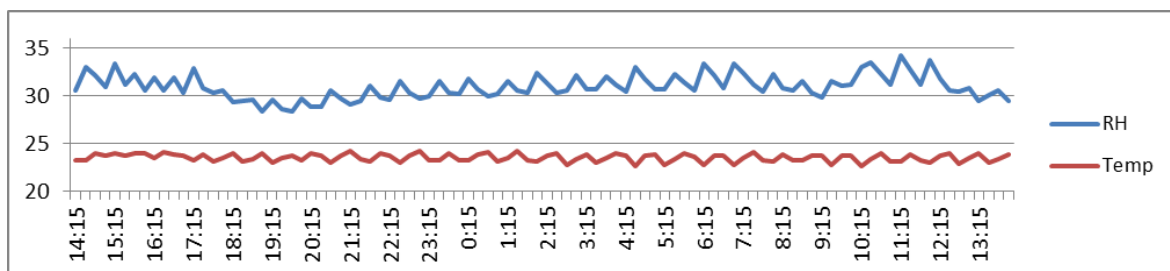


FIGURE 5. Measurements of 19 – 20 of November

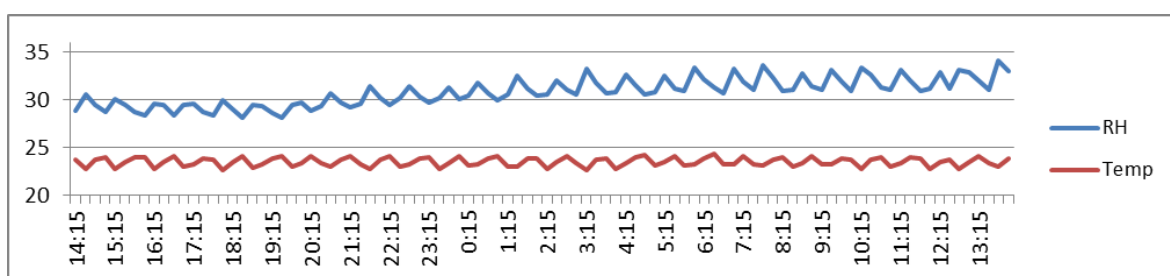


FIGURE 6. Measurements of 20 – 21 of November

APPENDIX 8(1)

Data Logger #3

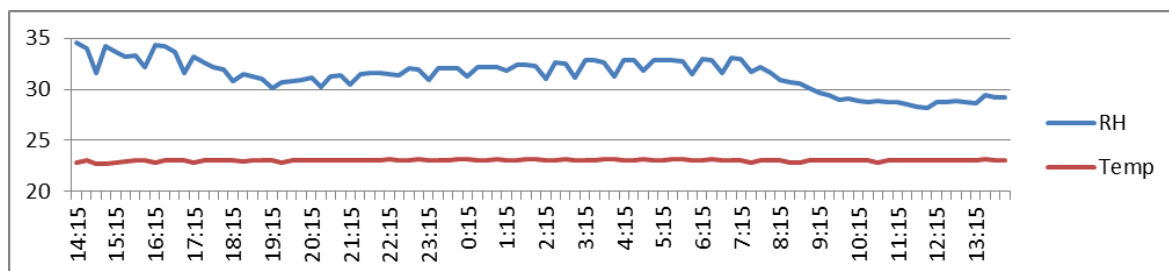


FIGURE 1. Measurements of 15 – 16 of November

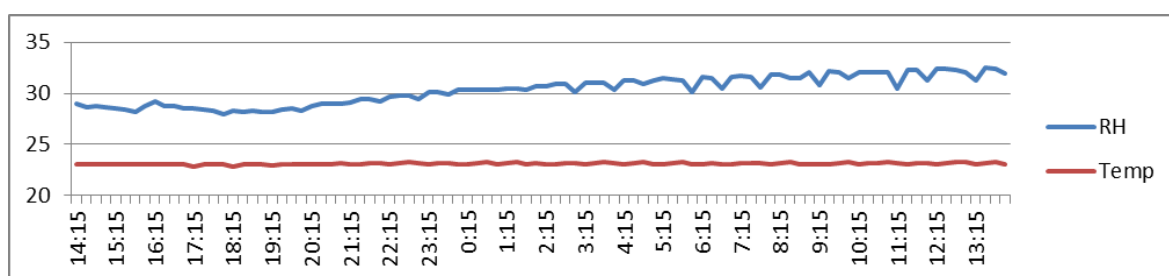


FIGURE 2. Measurements of 16 – 17 of November

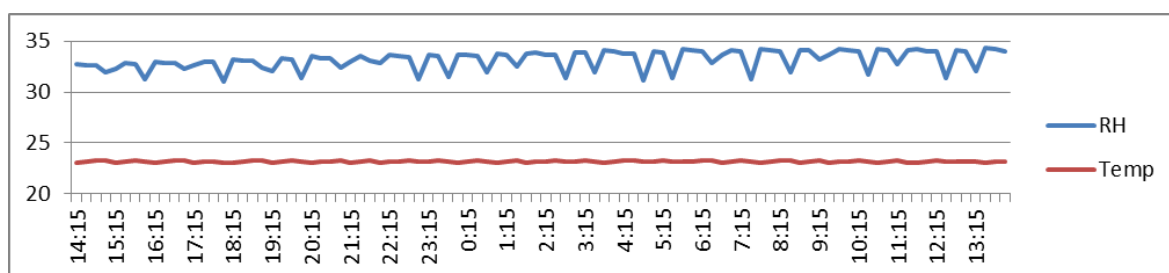


FIGURE 3. Measurements of 17 – 18 of November

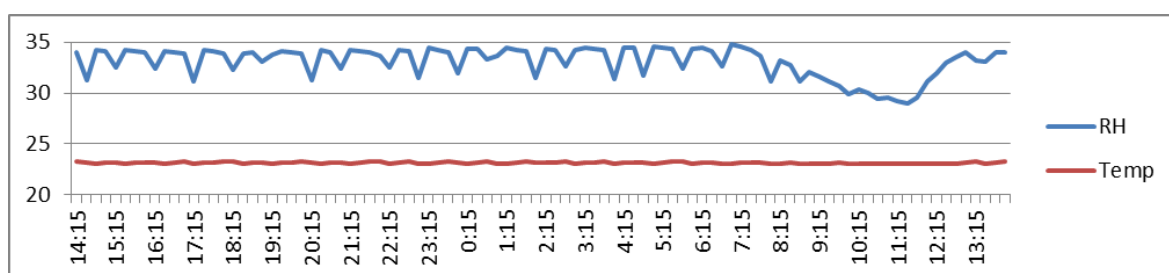


FIGURE 4. Measurements of 18 – 19 of November

APPENDIX 8(2)

Data Logger #3

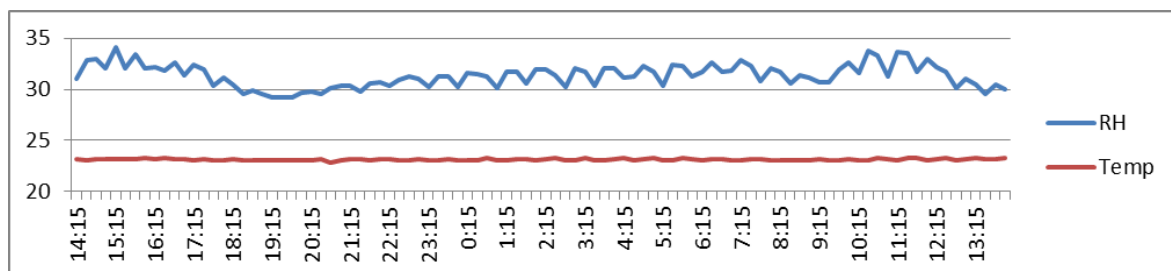


FIGURE 5. Measurements of 19 – 20 of November

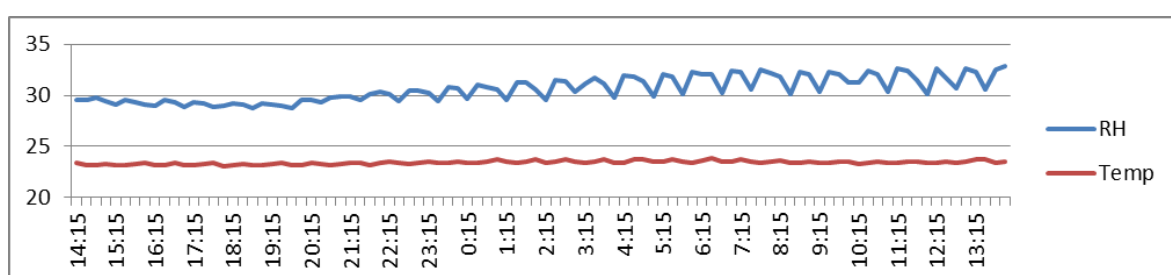


FIGURE 6. Measurements of 20 – 21 of November

APPENDIX 9(1)

Data Logger #4

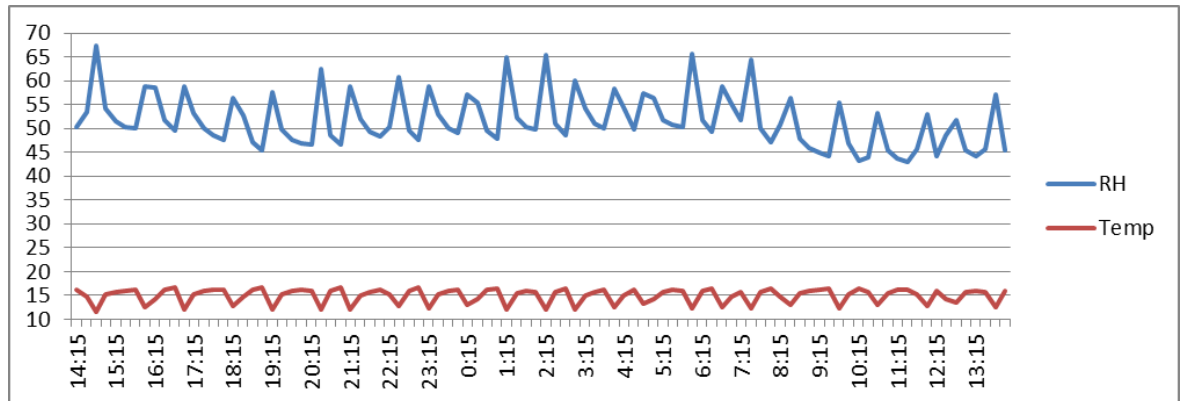


FIGURE 1. Measurements of 15 – 16 of November

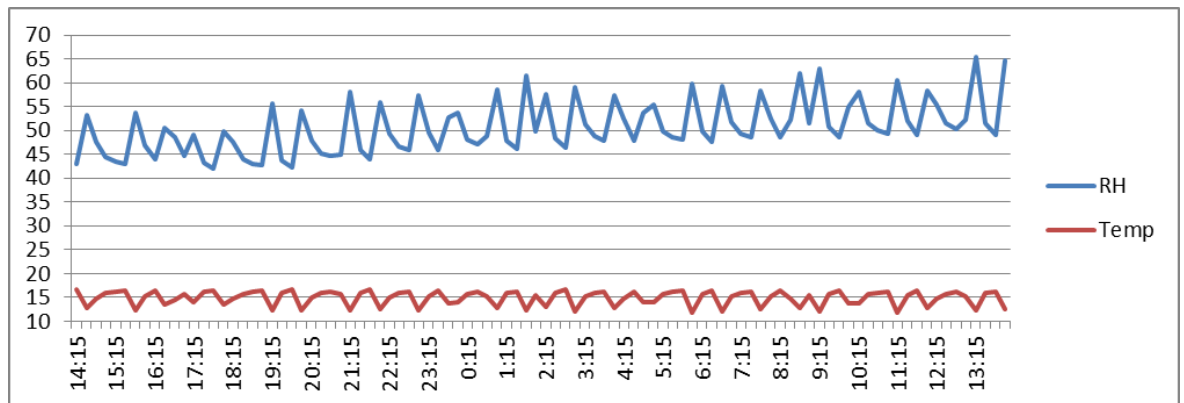


FIGURE 2. Measurements of 16 – 17 of November

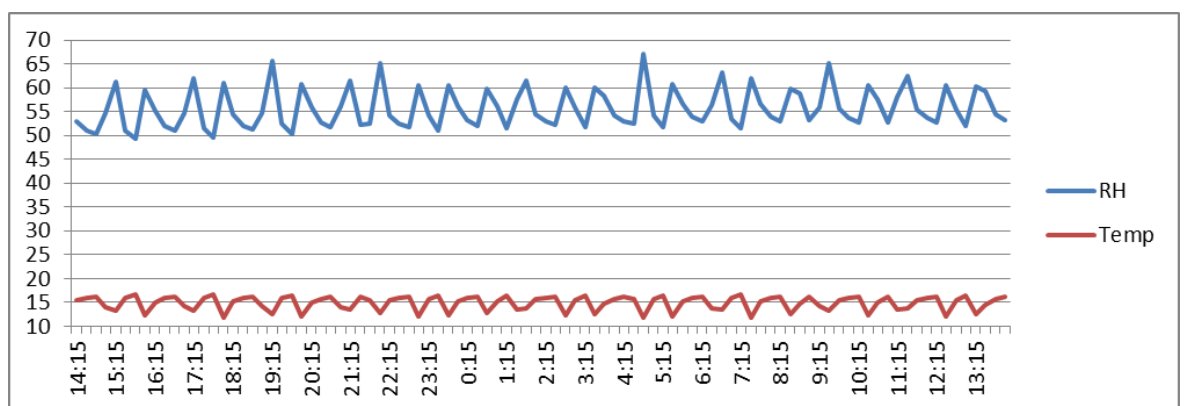


FIGURE 3. Measurements of 17 – 18 of November

APPENDIX 9(2)

Data Logger #4

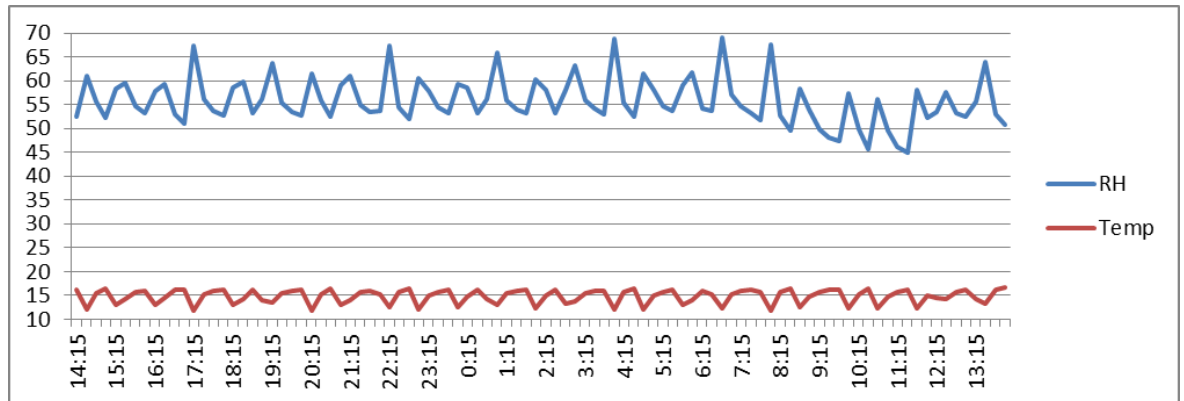


FIGURE 4. Measurements of 18 – 19 of November

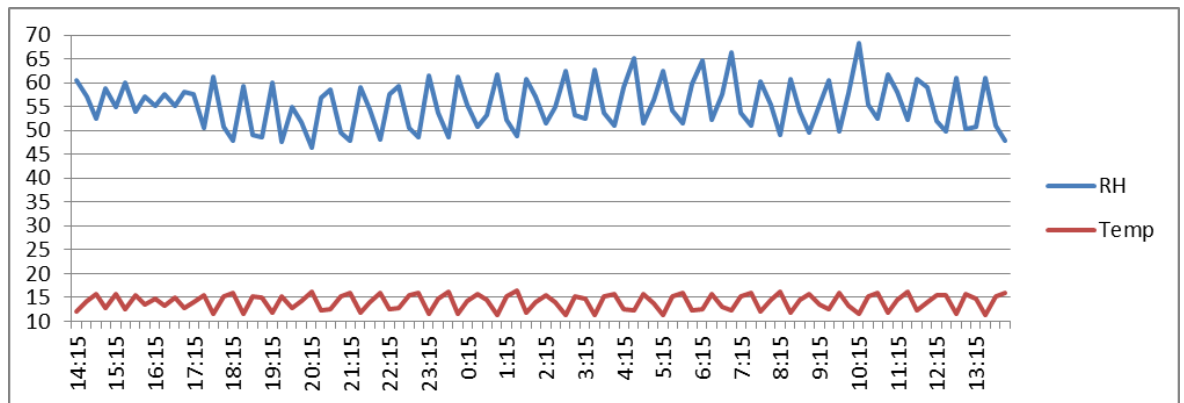


FIGURE 5. Measurements of 19 – 20 of November

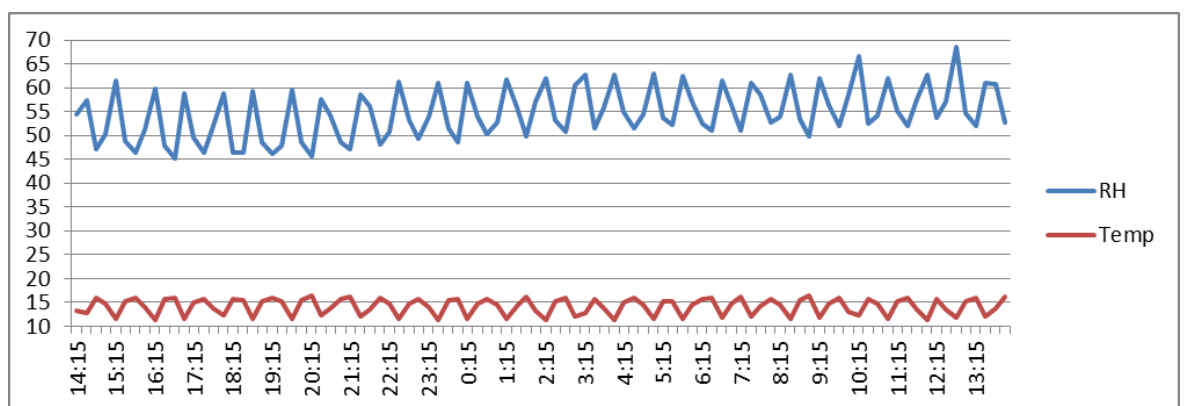


FIGURE 6. Measurements of 20 – 21 of November

APPENDIX 10(1)

Data Logger #5

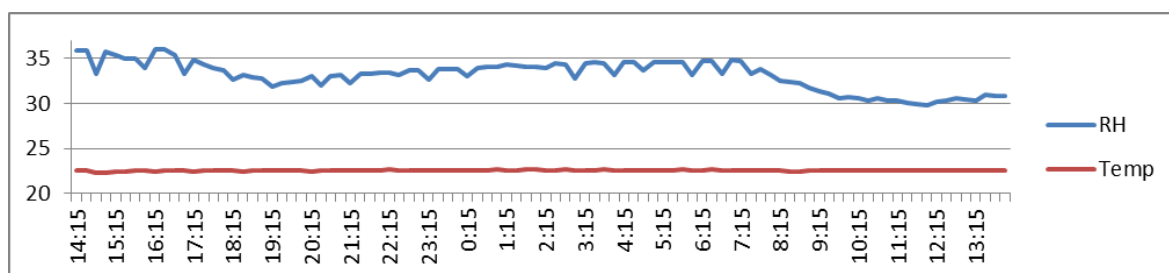


FIGURE 1. Measurements of 15 – 16 of November

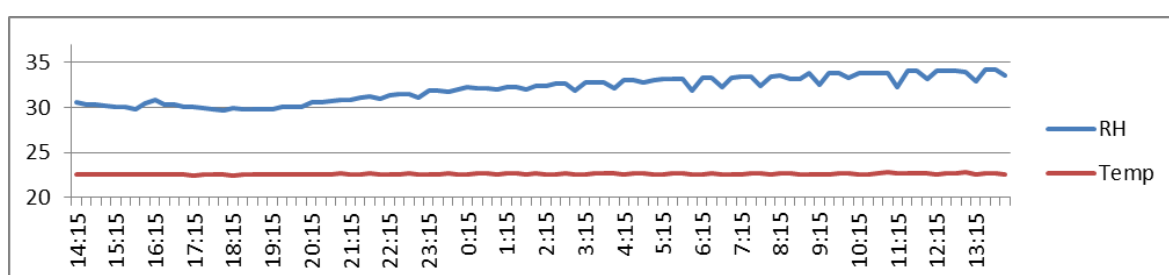


FIGURE 2. Measurements of 16 – 17 of November

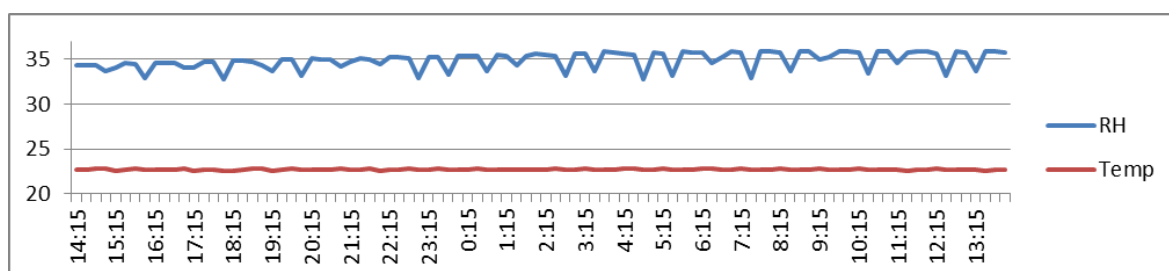


FIGURE 3. Measurements of 17 – 18 of November

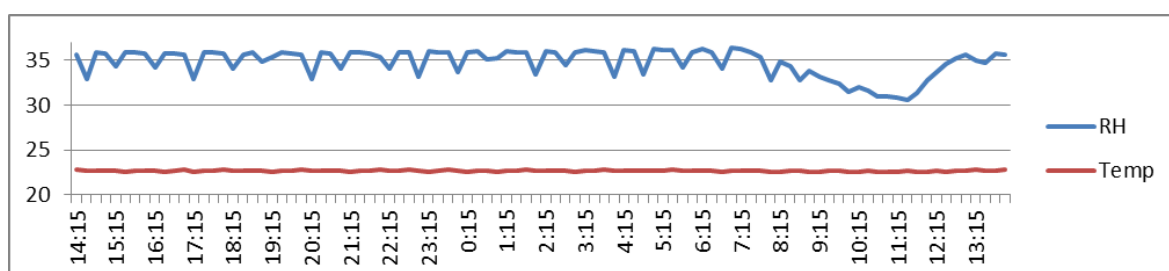


FIGURE 4. Measurements of 18 – 19 of November

APPENDIX 10(2)

Data Logger #5

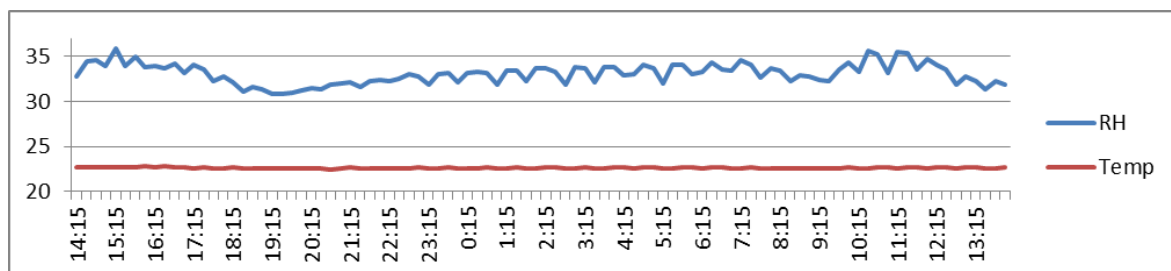


FIGURE 5. Measurements of 19 – 20 of November

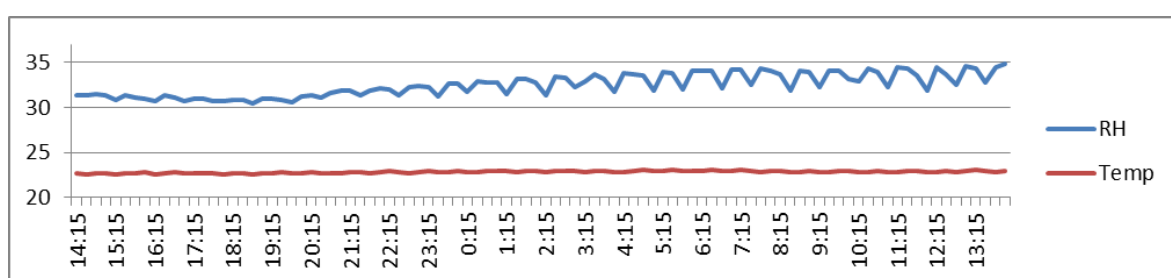


FIGURE 6. Measurements of 20 – 21 of November

APPENDIX 11(1)

Data Logger #6

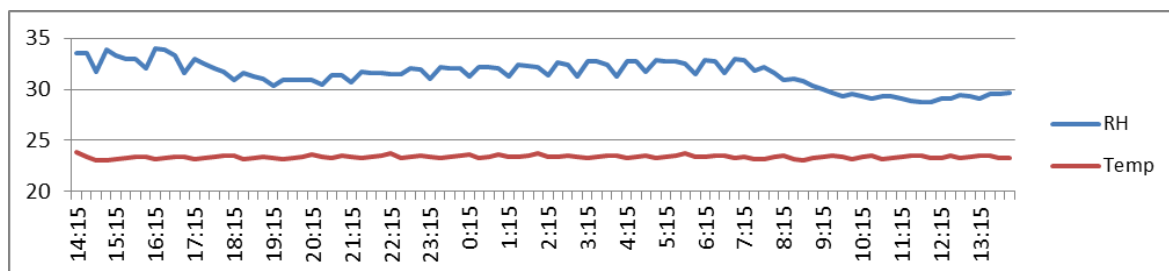


FIGURE 1. Measurements of 15 – 16 of November

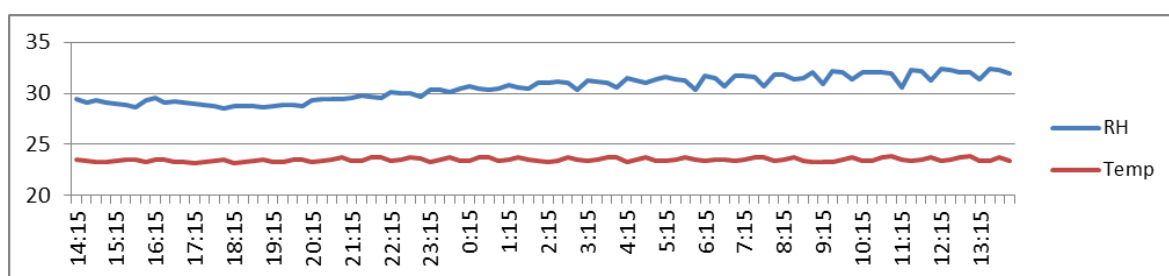


FIGURE 2. Measurements of 16 – 17 of November

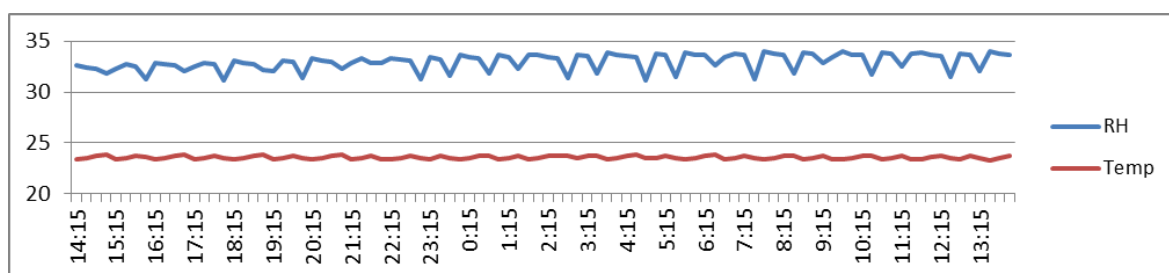


FIGURE 3. Measurements of 17 – 18 of November

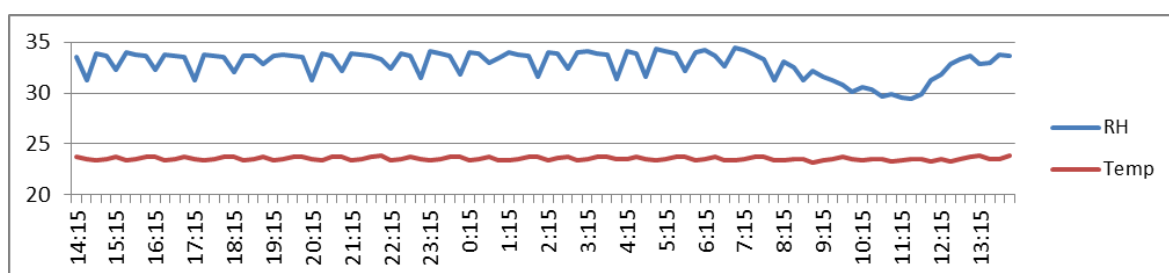


FIGURE 4. Measurements of 18 – 19 of November

APPENDIX 11(2)

Data Logger #6

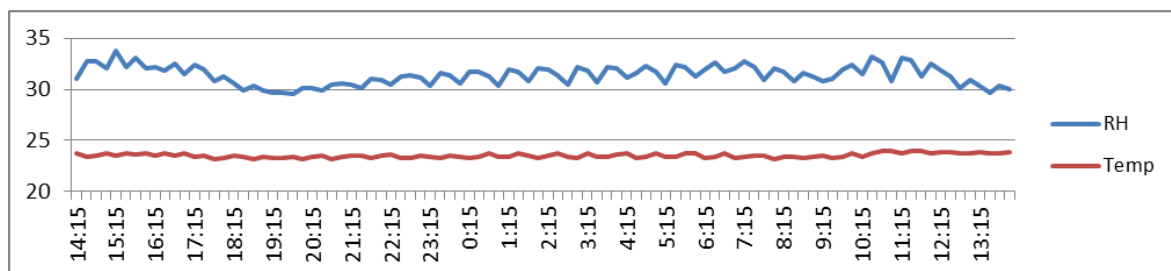


FIGURE 5. Measurements of 19 – 20 of November

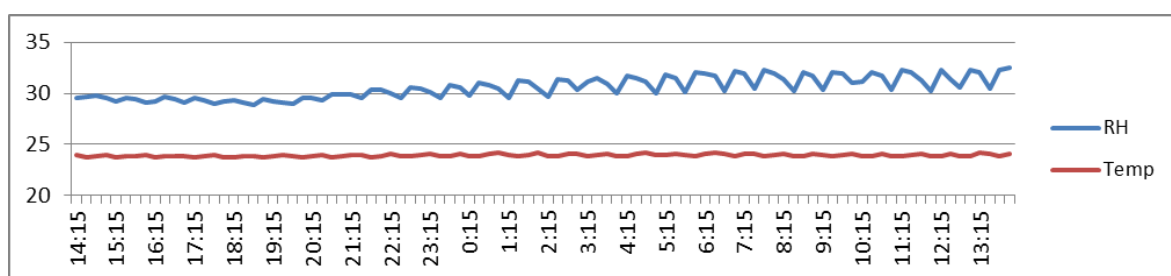


FIGURE 6. Measurements of 20 – 21 of November

APPENDIX 12(1)

Data Logger #7

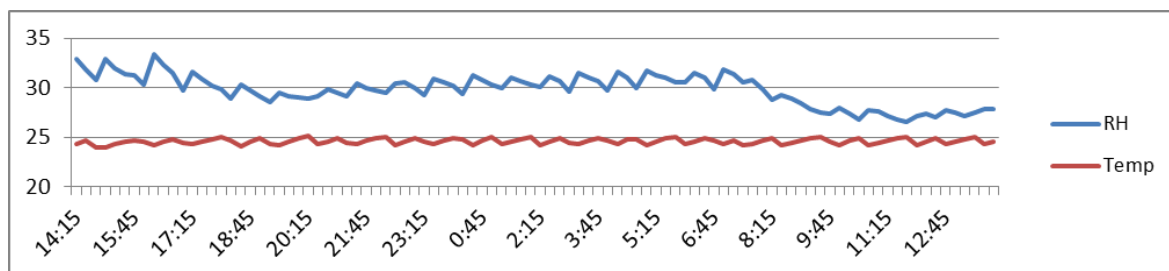


FIGURE 1. Measurements of 15 – 16 of November

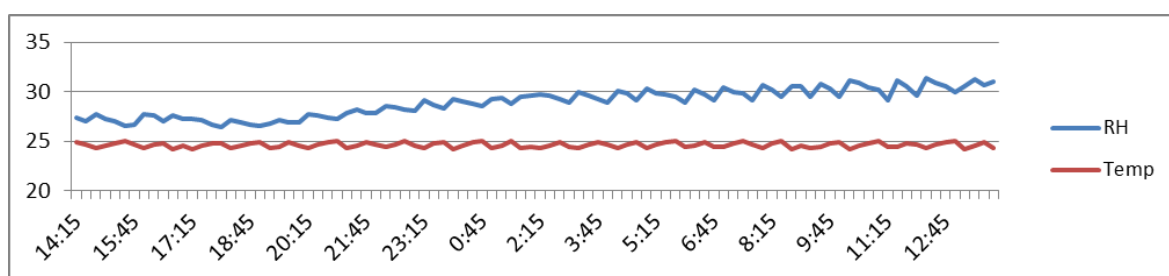


FIGURE 2. Measurements of 16 – 17 of November

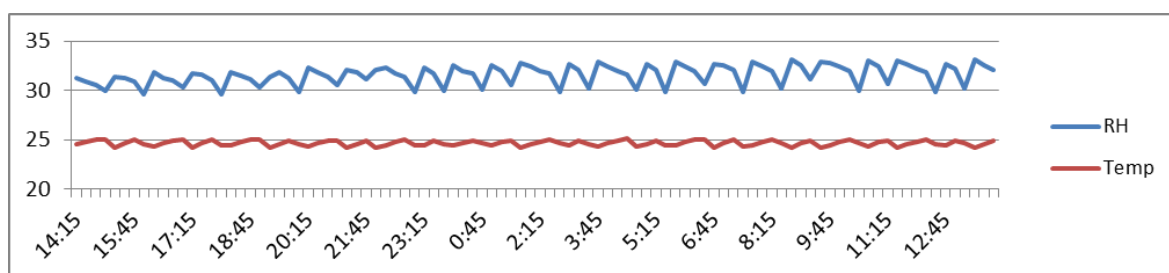


FIGURE 3. Measurements of 17 – 18 of November

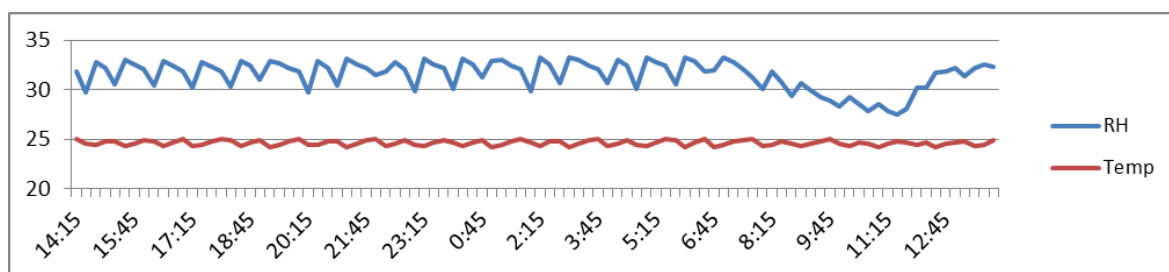


FIGURE 4. Measurements of 18 – 19 of November

APPENDIX 12(2)

Data Logger #7

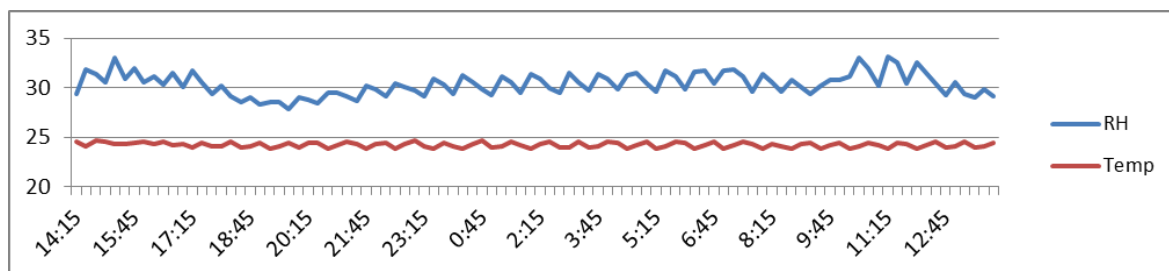


FIGURE 5. Measurements of 19 – 20 of November

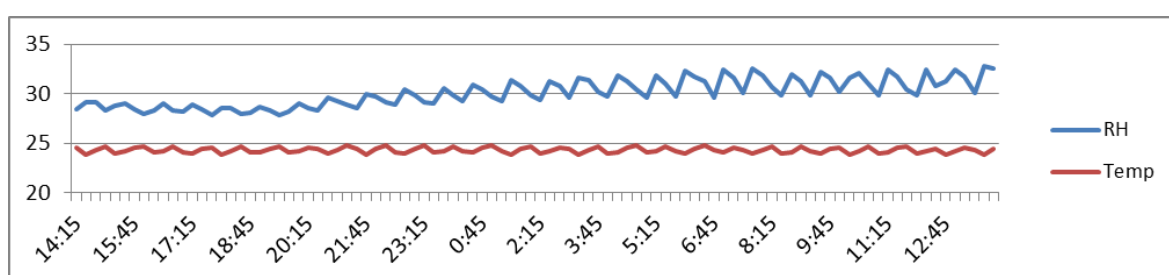


FIGURE 6. Measurements of 20 – 21 of November

APPENDIX 13(1)

Data Logger #8

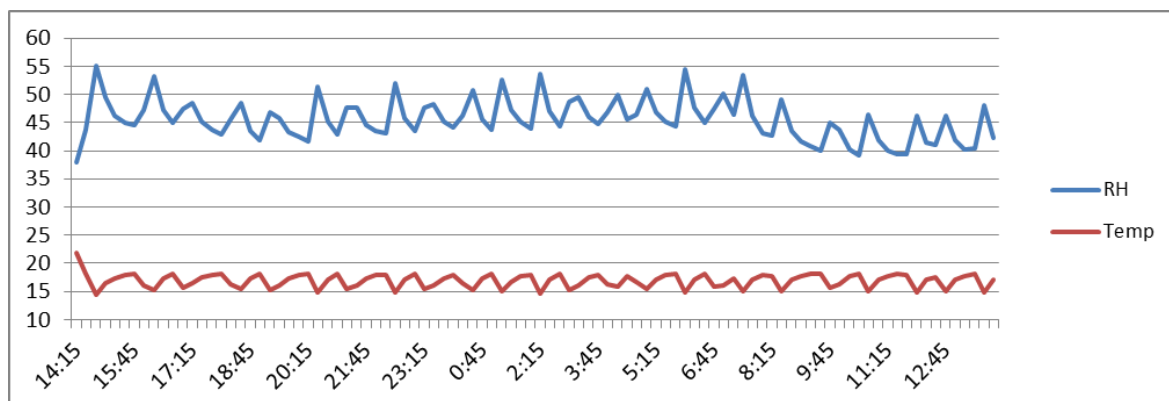


FIGURE 1. Measurements of 15 – 16 of November

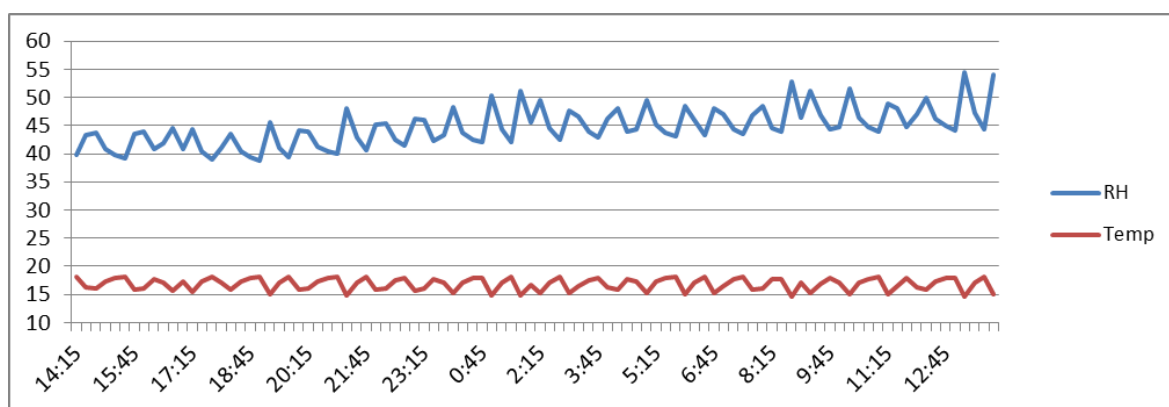


FIGURE 2. Measurements of 16 – 17 of November

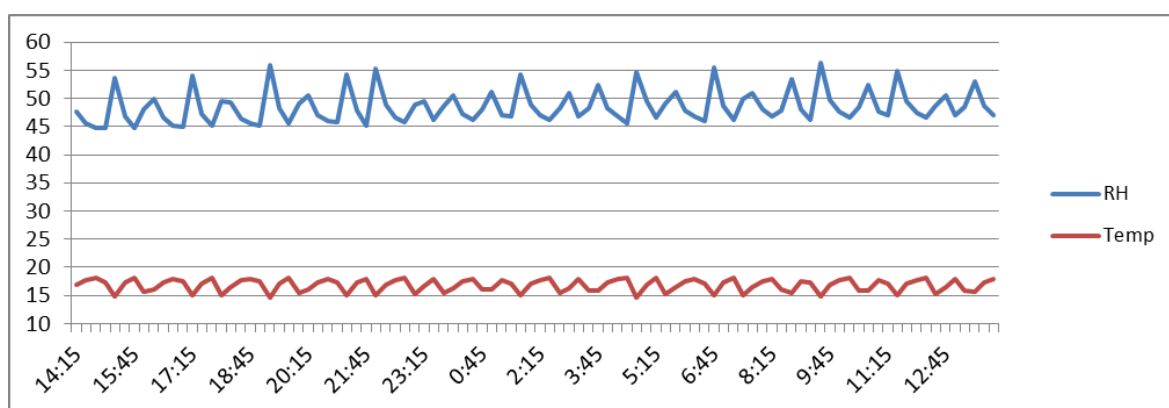


FIGURE 3. Measurements of 17 – 18 of November

APPENDIX 13(2)

Data Logger #8

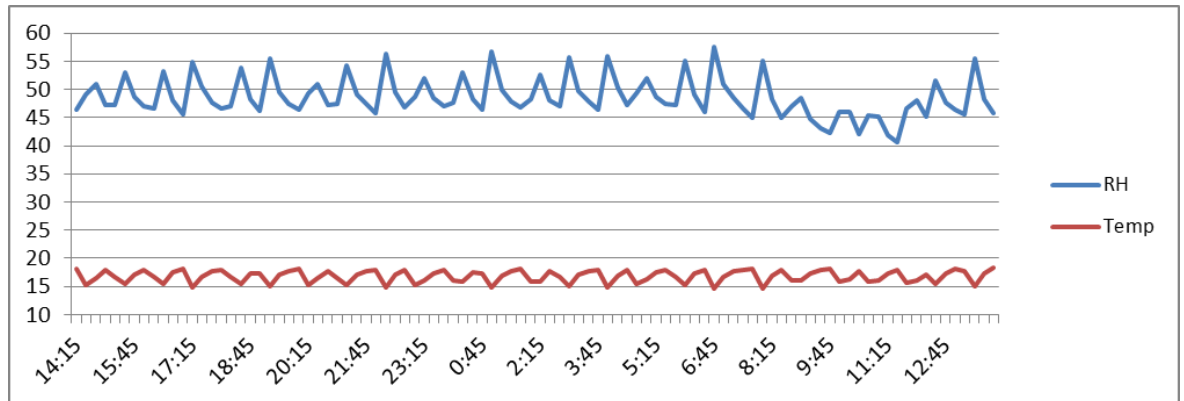


FIGURE 4. Measurements of 18 – 19 of November

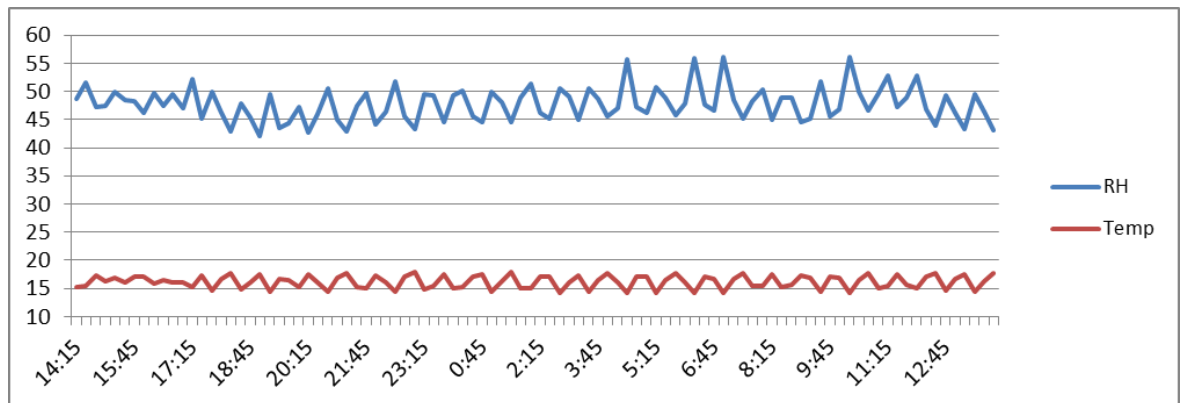


FIGURE 5. Measurements of 19 – 20 of November

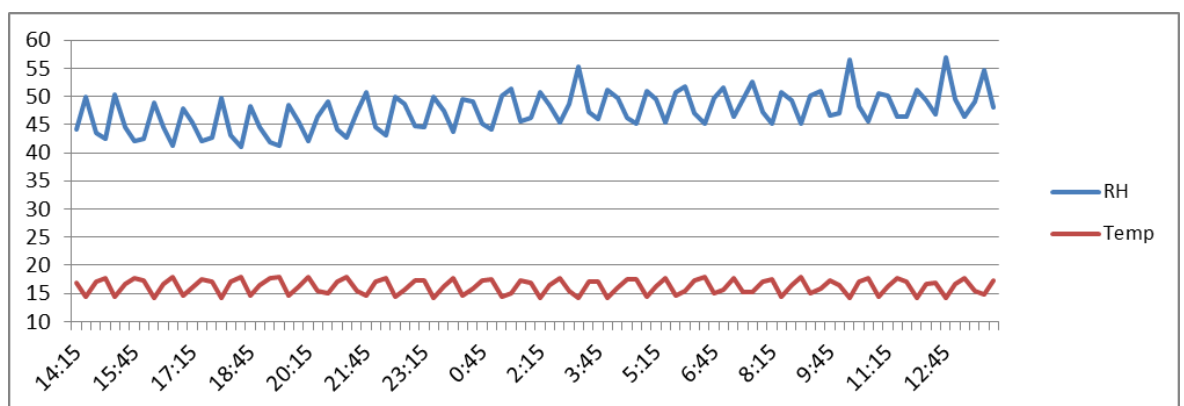


FIGURE 6. Measurements of 20 – 21 of November

APPENDIX 14(1)

Data Logger #9

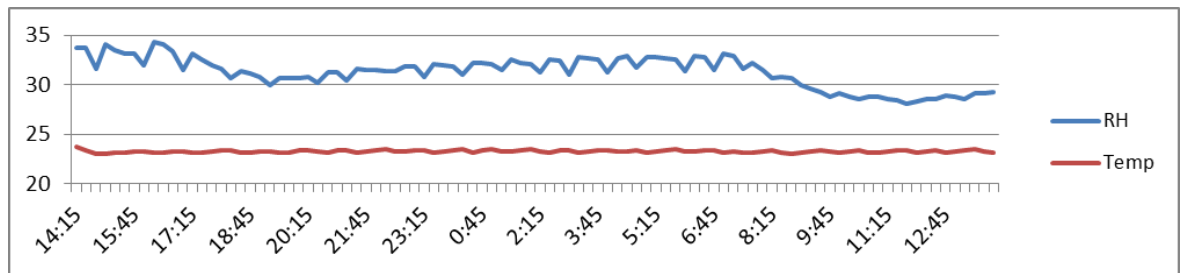


FIGURE 1. Measurements of 15 – 16 of November.

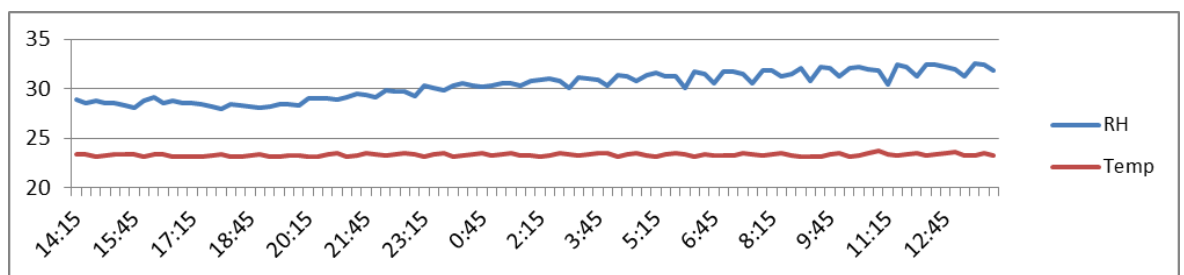


FIGURE 2. Measurements of 16 – 17 of November

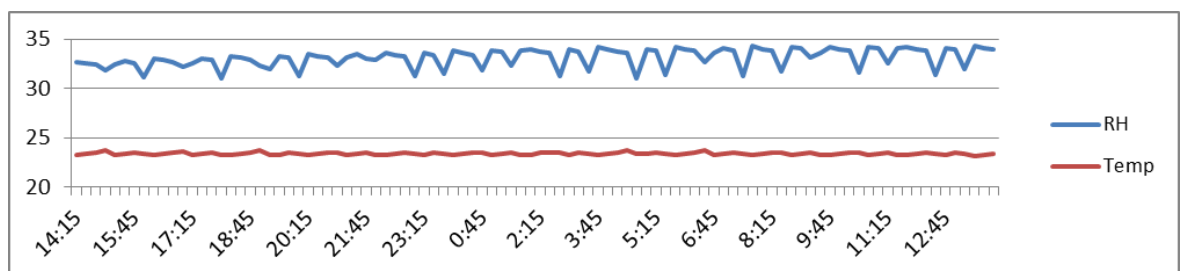


FIGURE 3. Measurements of 17 – 18 of November

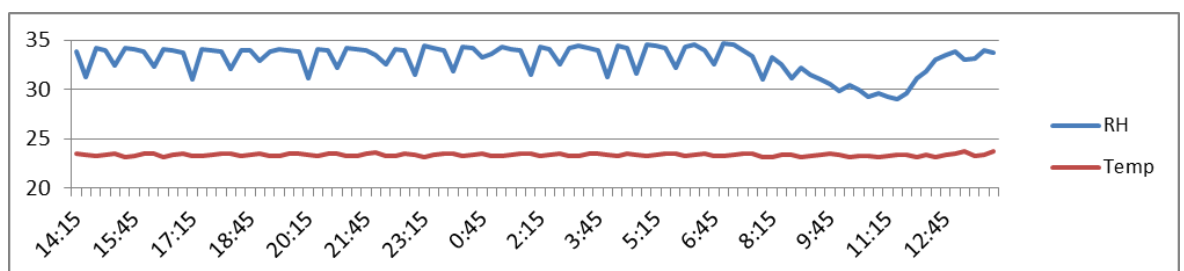


FIGURE 4. Measurements of 18 – 19 of November

APPENDIX 14(2)

Data Logger #9

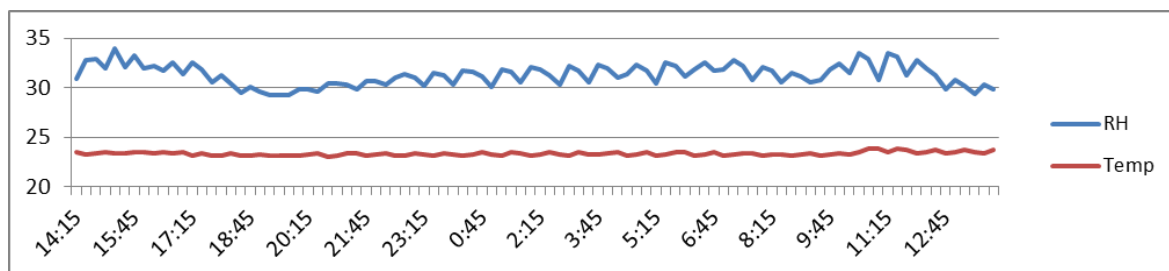


FIGURE 5. Measurements of 19 – 20 of November

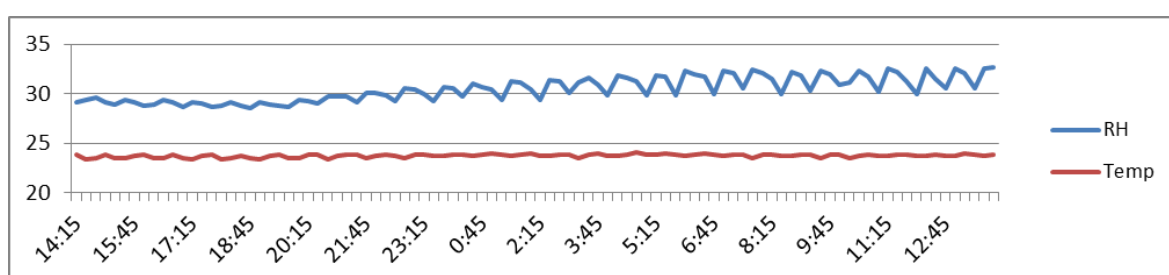


FIGURE 6. Measurements of 20 – 21 of November

APPENDIX 15(1)

Data Logger #10

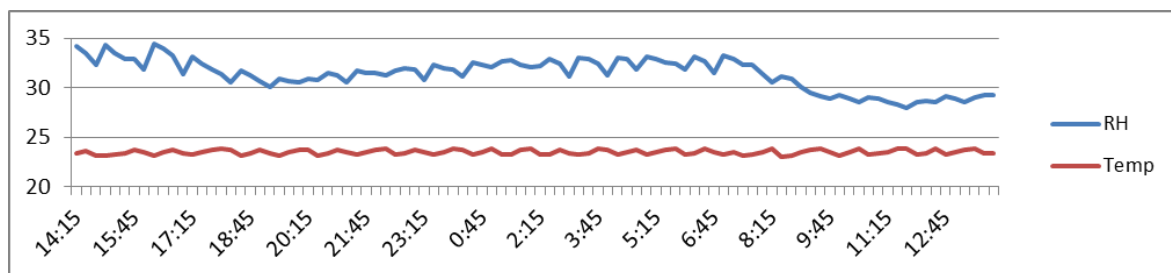


FIGURE 1. Measurements of 15 – 16 of November

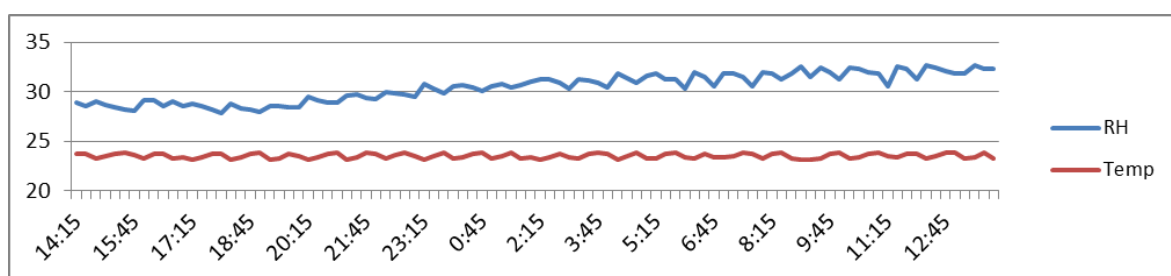


FIGURE 2. Measurements of 16 – 17 of November

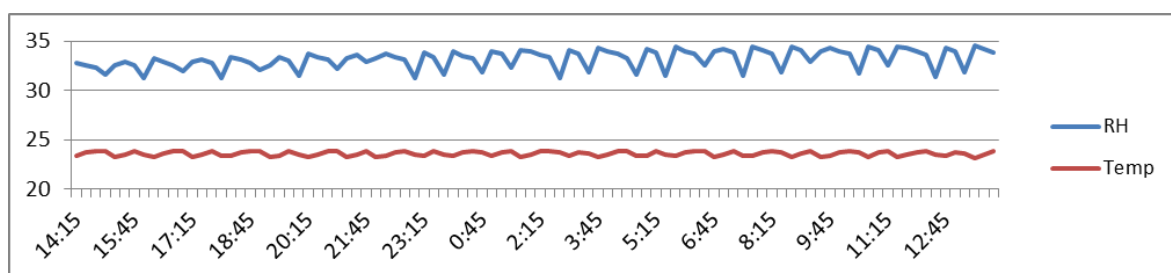


FIGURE 3. Measurements of 17 – 18 of November

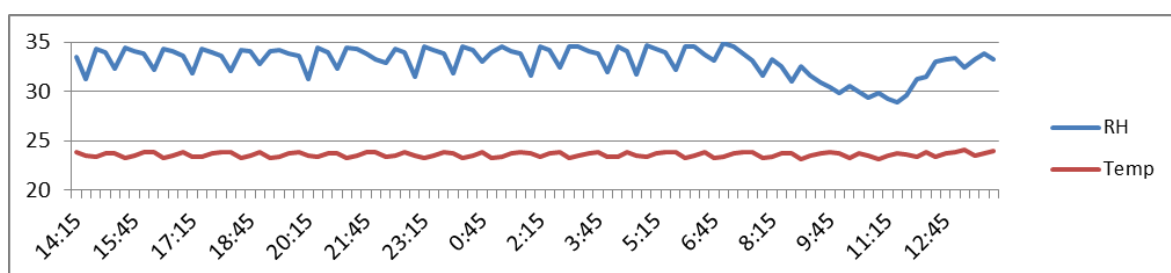


FIGURE 4. Measurements of 18 – 19 of November

APPENDIX 15(2)

Data Logger #10

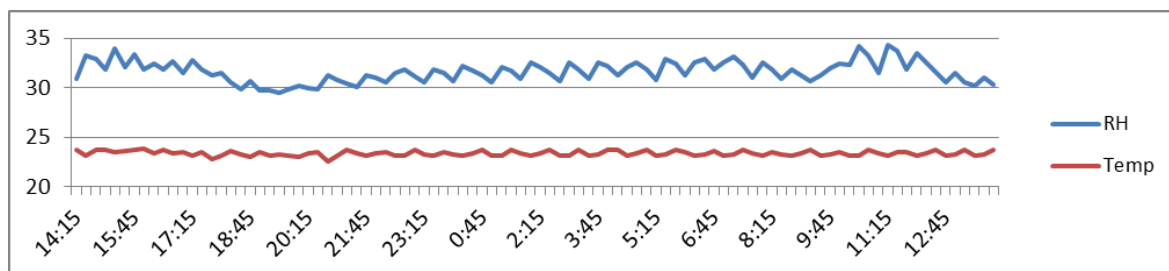


FIGURE 5. Measurements of 19 – 20 of November

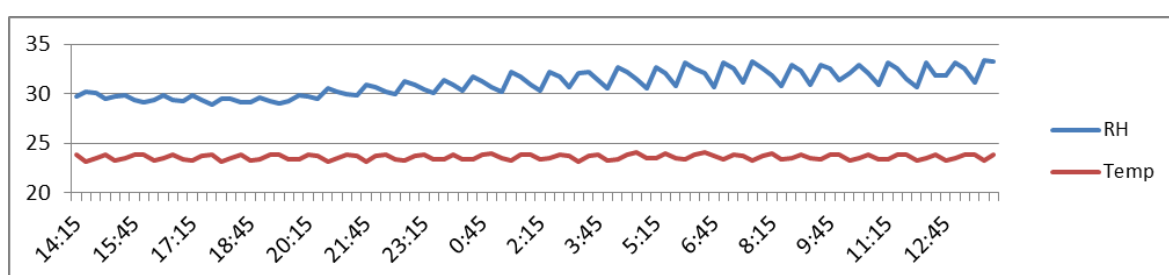


FIGURE 6. Measurements of 20 – 21 of November

APPENDIX 16(1)

Data Logger #11

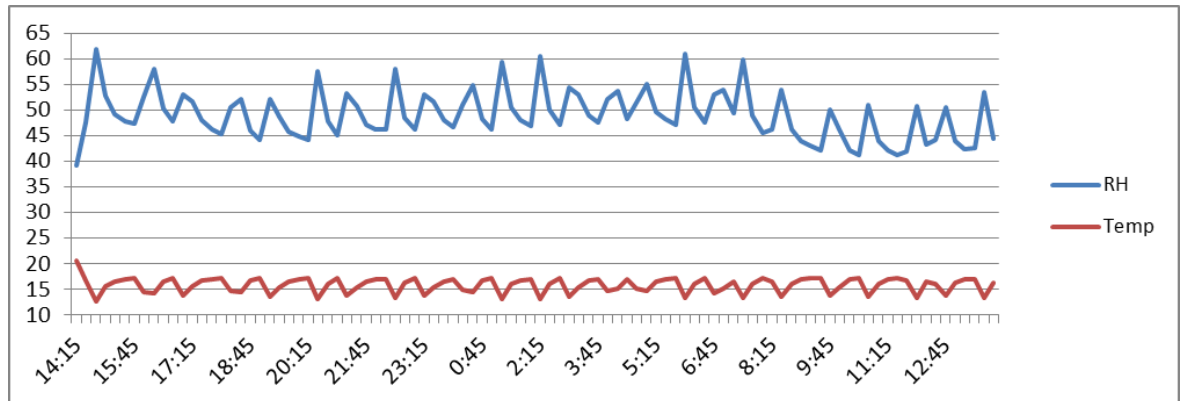


FIGURE 1. Measurements of 15 – 16 of November

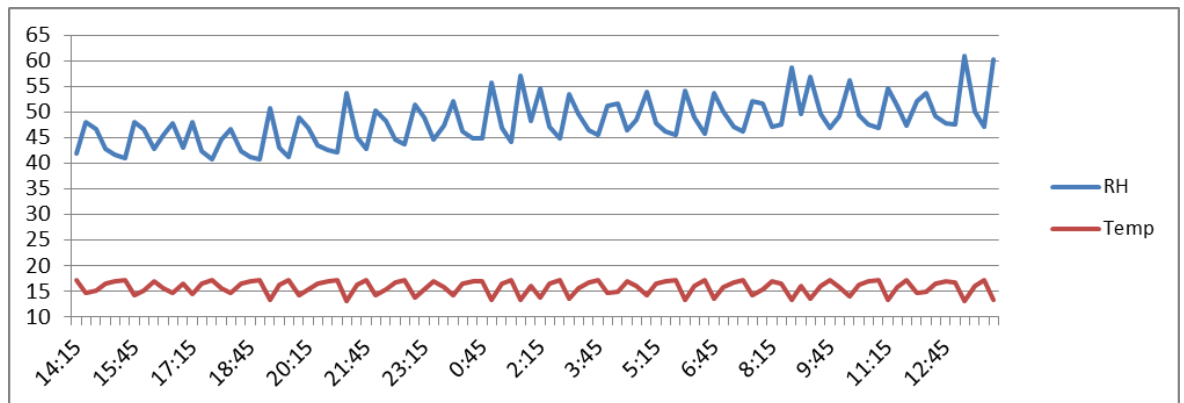


FIGURE 2. Measurements of 16 – 17 of November

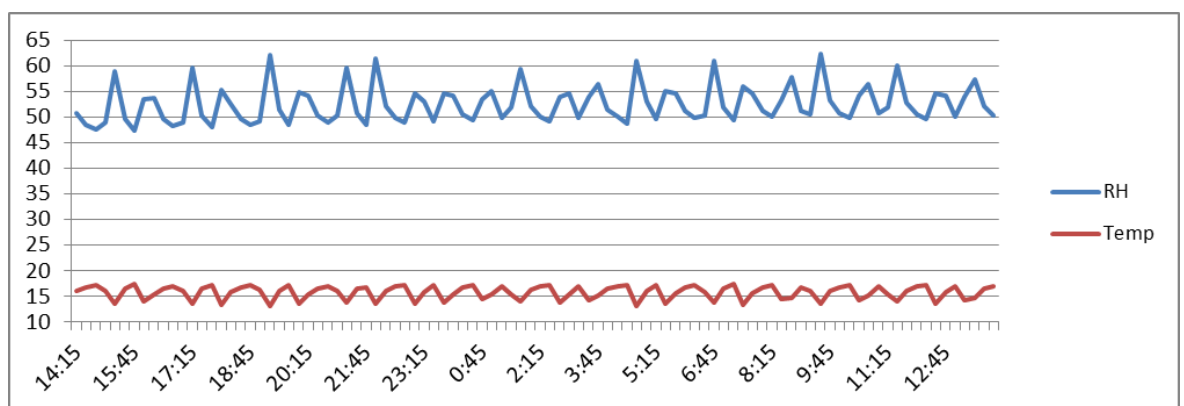


FIGURE 3. Measurements of 17 – 18 of November

APPENDIX 16(2)

Data Logger #11

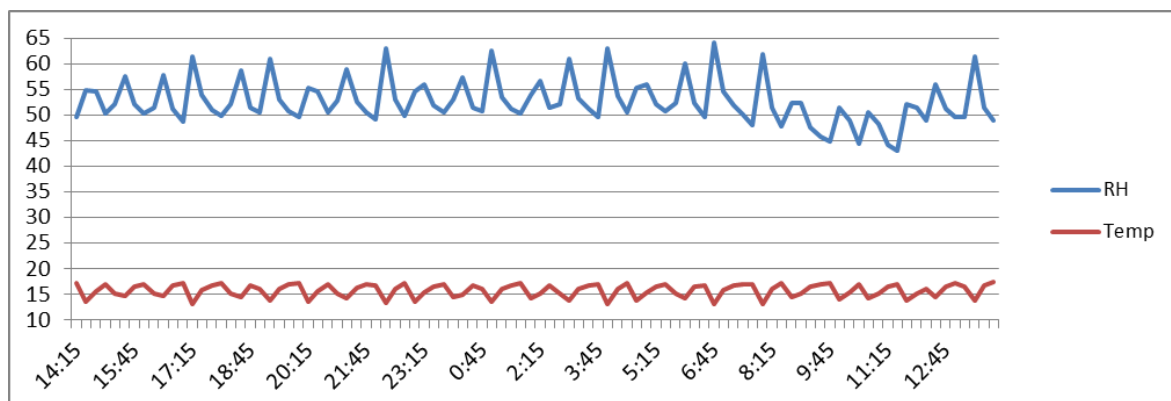


FIGURE 4. Measurements of 18 – 19 of November

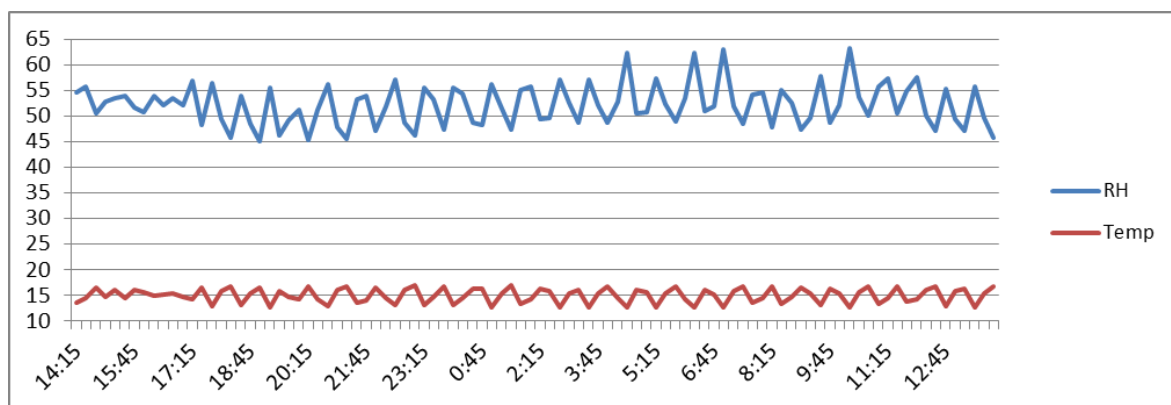


FIGURE 5. Measurements of 19 – 20 of November

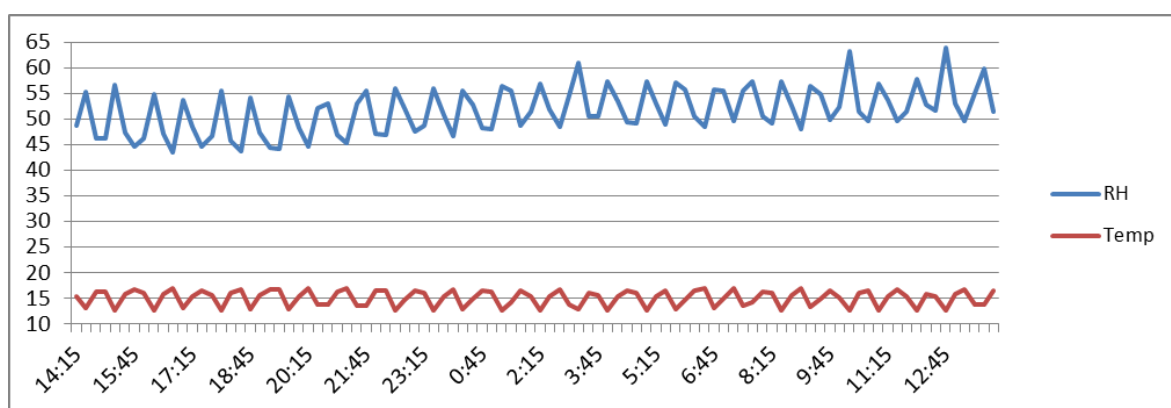


FIGURE 6. Measurements of 20 – 21 of November

APPENDIX 17(1)

Data Logger #12

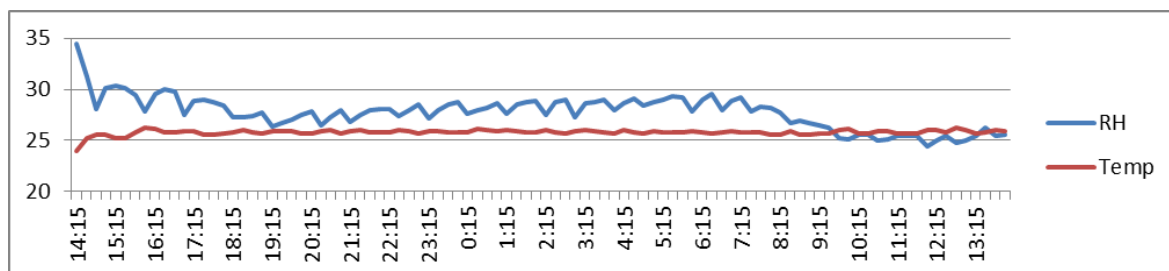


FIGURE 1. Measurements of 15 – 16 of November

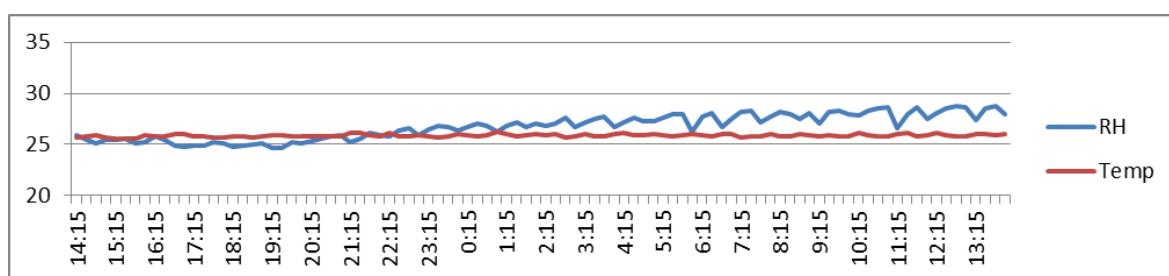


FIGURE 2. Measurements of 16 – 17 of November

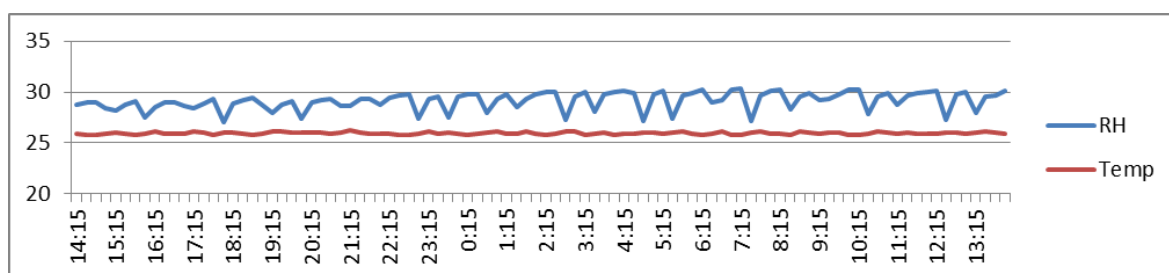


FIGURE 3. Measurements of 17 – 18 of November

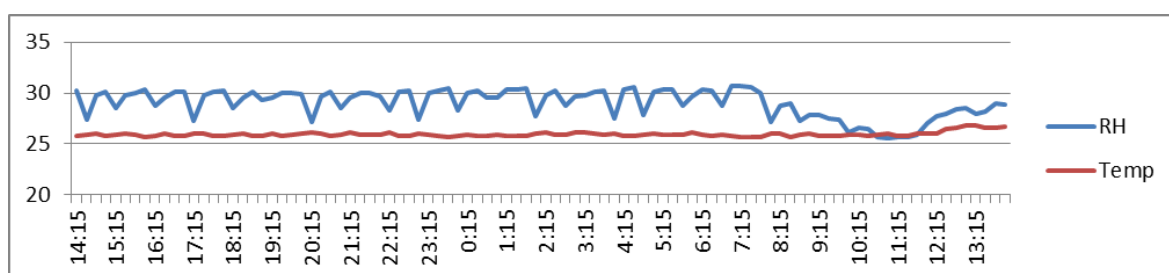


FIGURE 4. Measurements of 18 – 19 of November

APPENDIX 17(2)

Data Logger #12

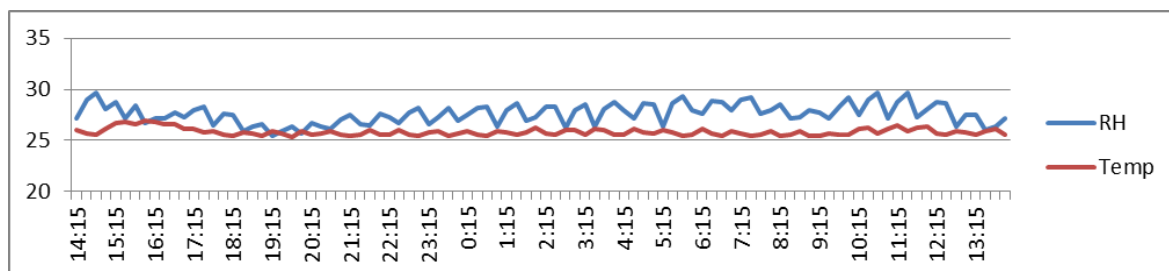


FIGURE 5. Measurements of 19 – 20 of November

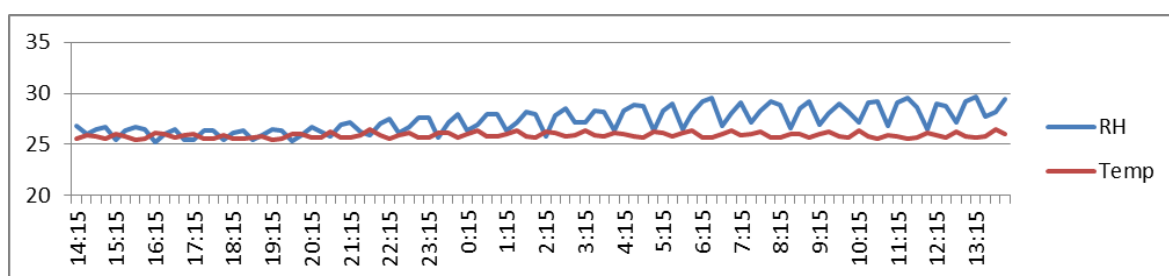


FIGURE 6. Measurements of 20 – 21 of November

APPENDIX 18(1)

Data Logger #13

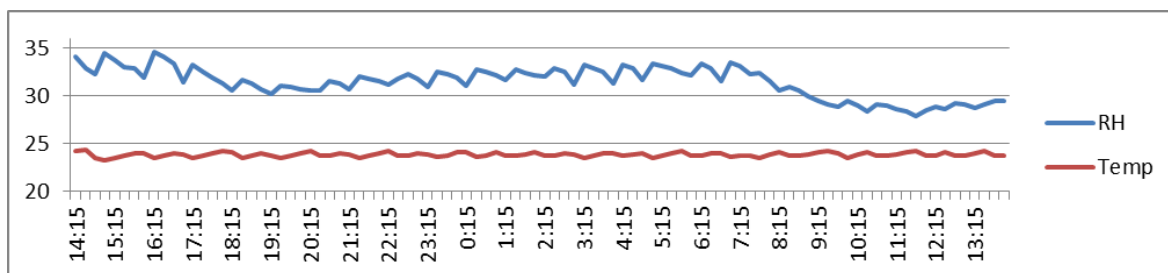


FIGURE 1. Measurements of 15 – 16 of November

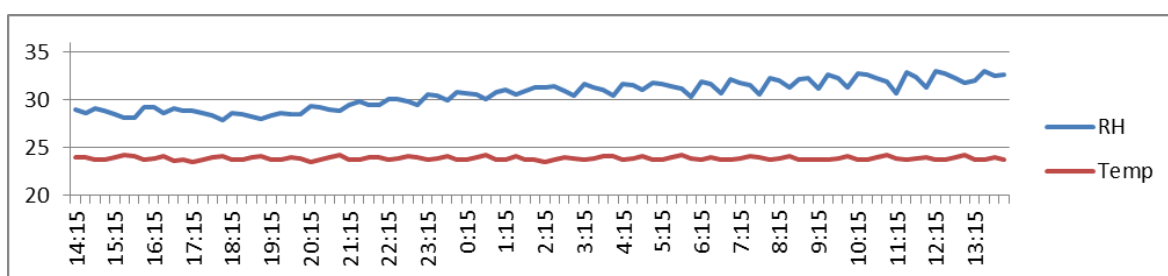


FIGURE 2. Measurements of 16 – 17 of November

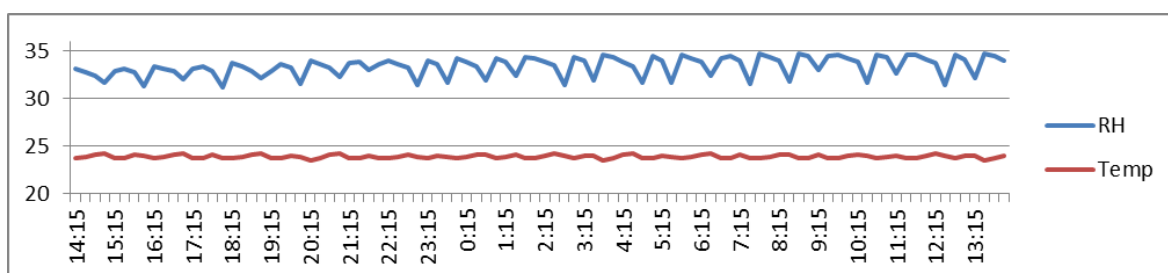


FIGURE 3. Measurements of 17 – 18 of November

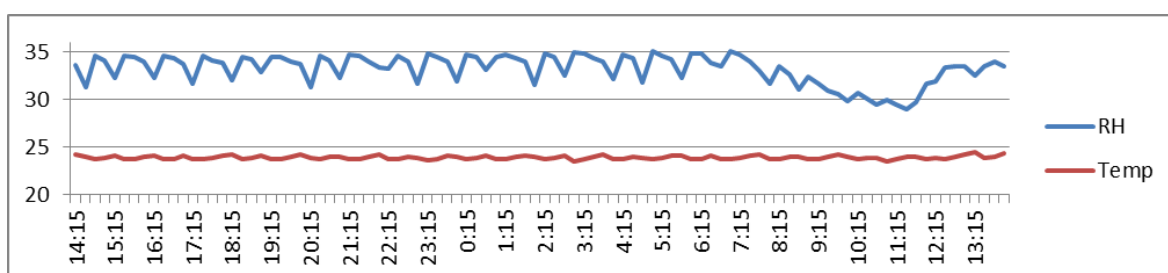


FIGURE 4. Measurements of 18 – 19 of November

APPENDIX 18(2)

Data Logger #13

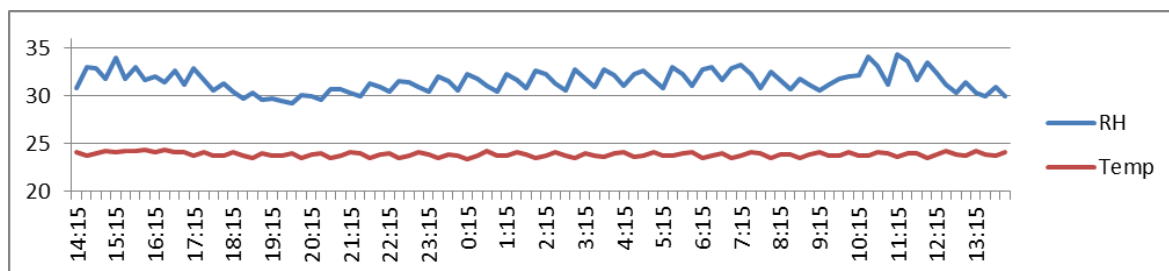


FIGURE 5. Measurements of 19 – 20 of November

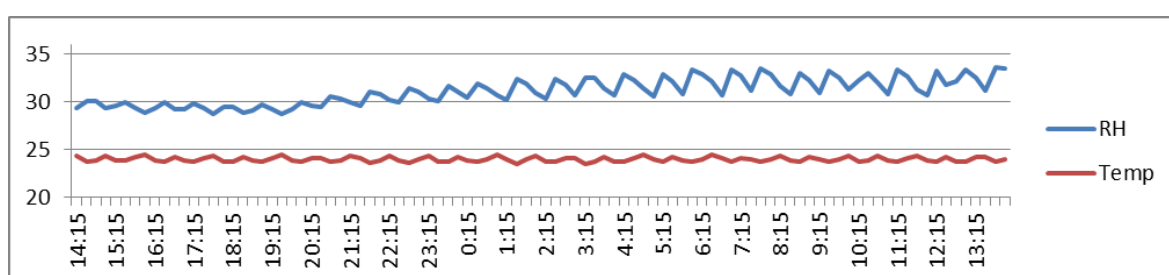


FIGURE 6. Measurements of 20 – 21 of November.

APPENDIX 19(1)

Data Logger #14

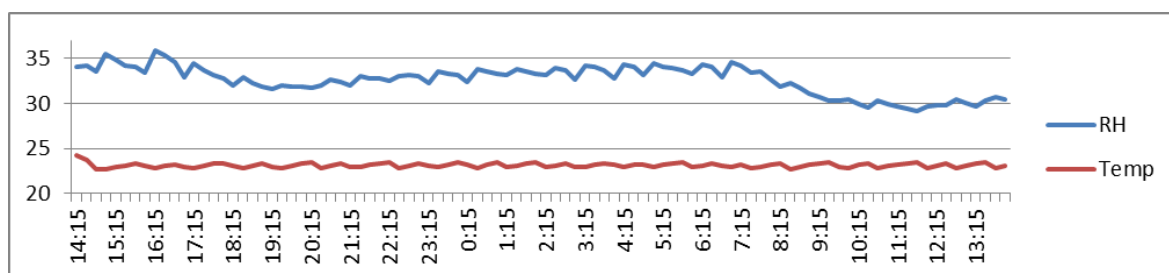


FIGURE 1. Measurements of 15 – 16 of November

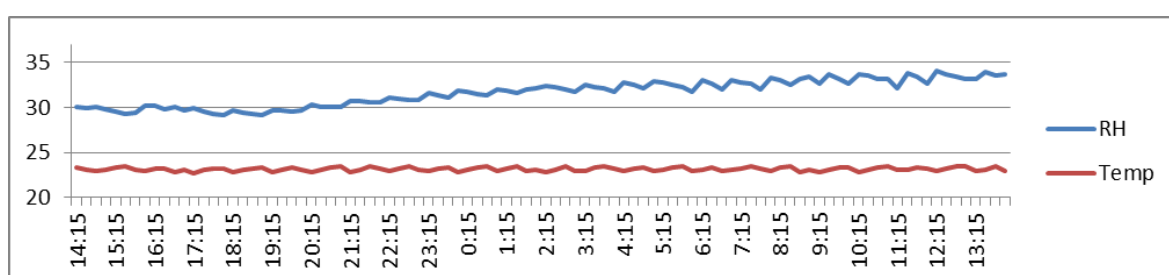


FIGURE 2. Measurements of 16 – 17 of November

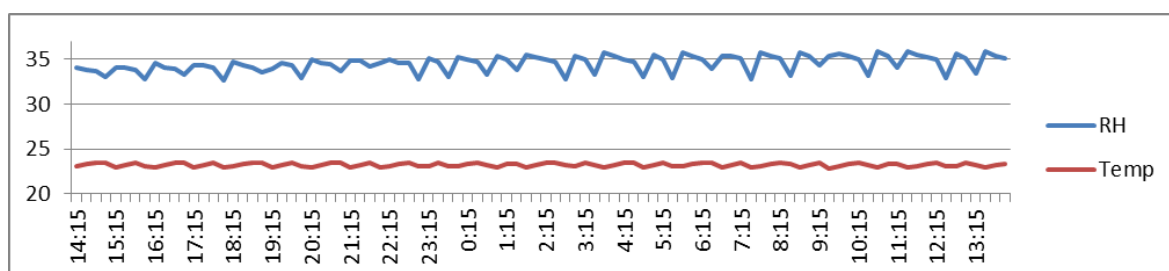


FIGURE 3. Measurements of 17 – 18 of November

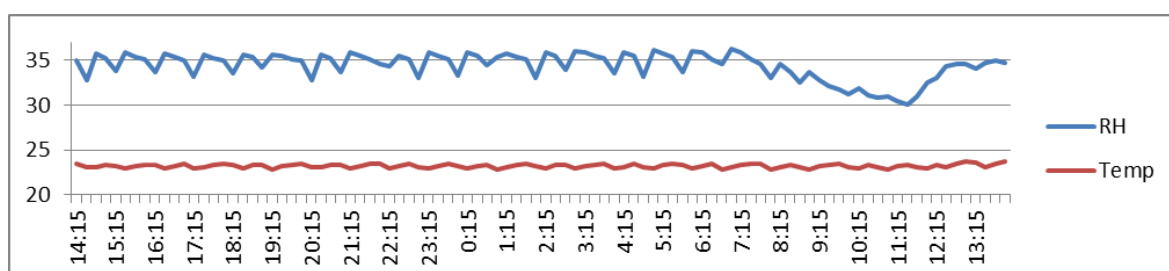


FIGURE 4. Measurements of 18 – 19 of November

APPENDIX 19(2)

Data Logger #14

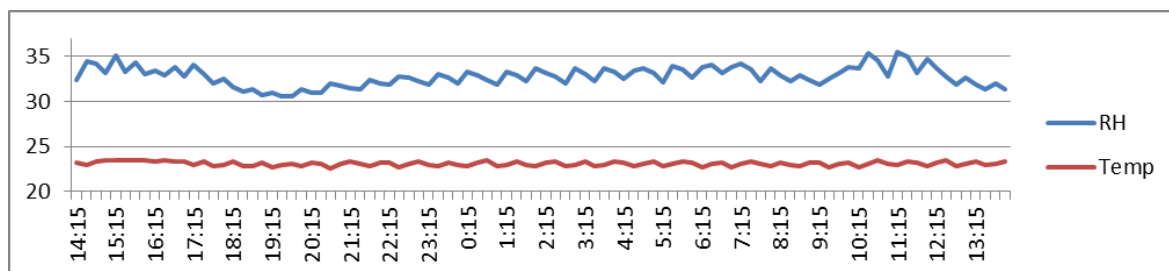


FIGURE 5. Measurements of 19 – 20 of November

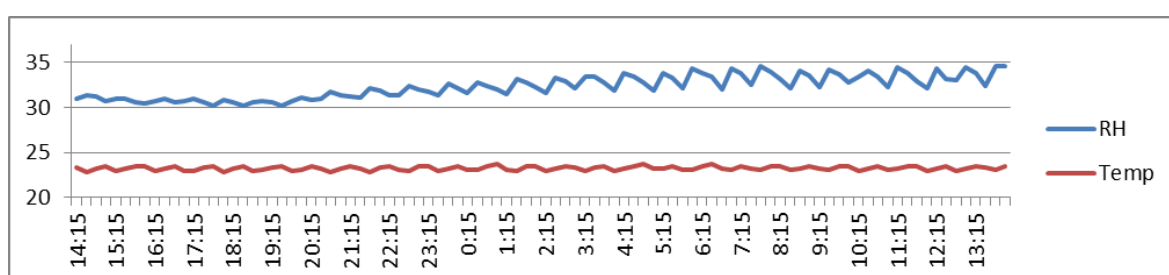


FIGURE 6. Measurements of 20 – 21 of November

APPENDIX 20(1)

Data Logger #15

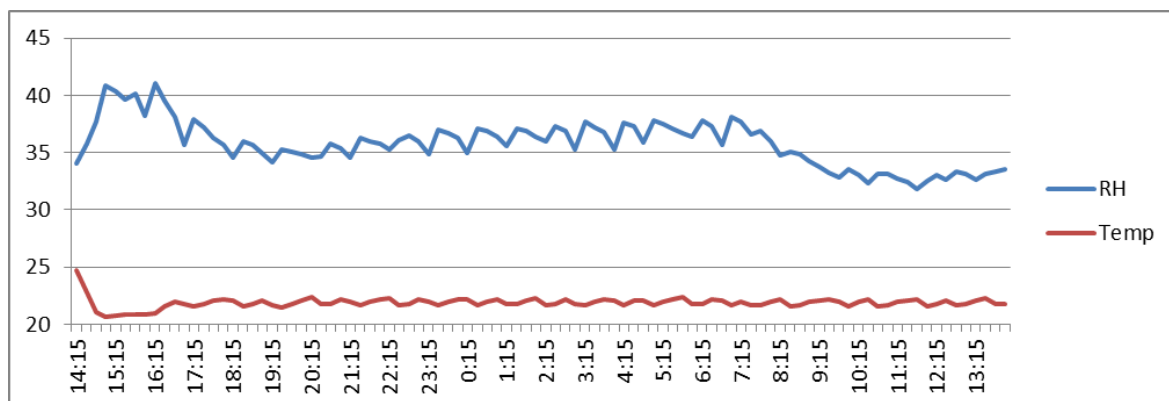


FIGURE 1. Measurements of 15 – 16 of November

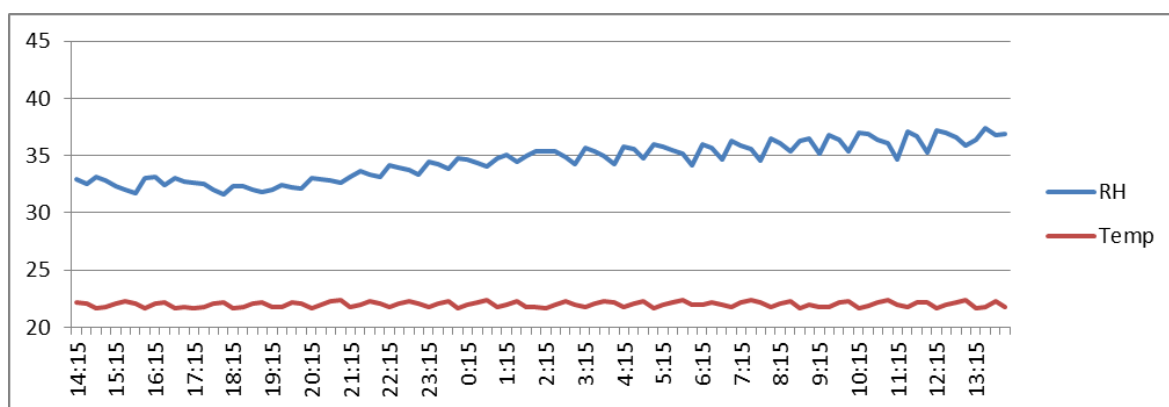


FIGURE 2. Measurements of 16 – 17 of November

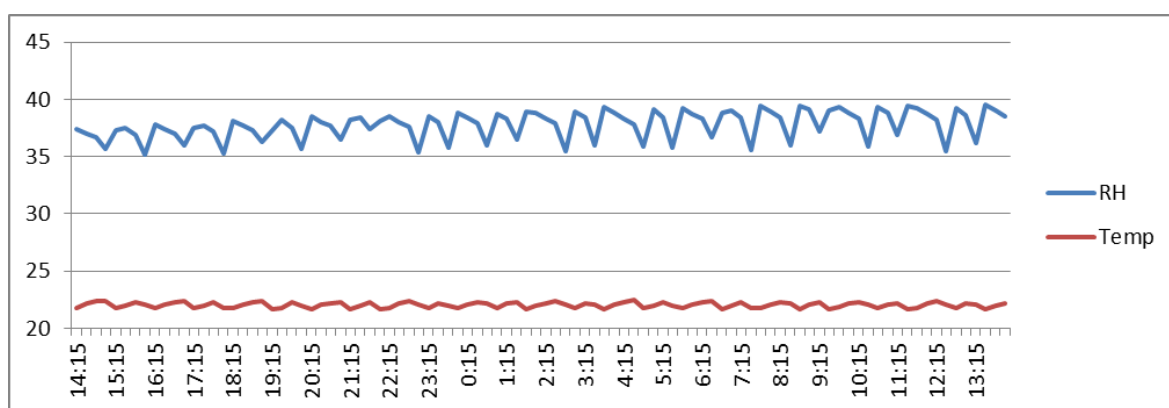


FIGURE 3. Measurements of 17 – 18 of November

APPENDIX 20(2)

Data Logger #15

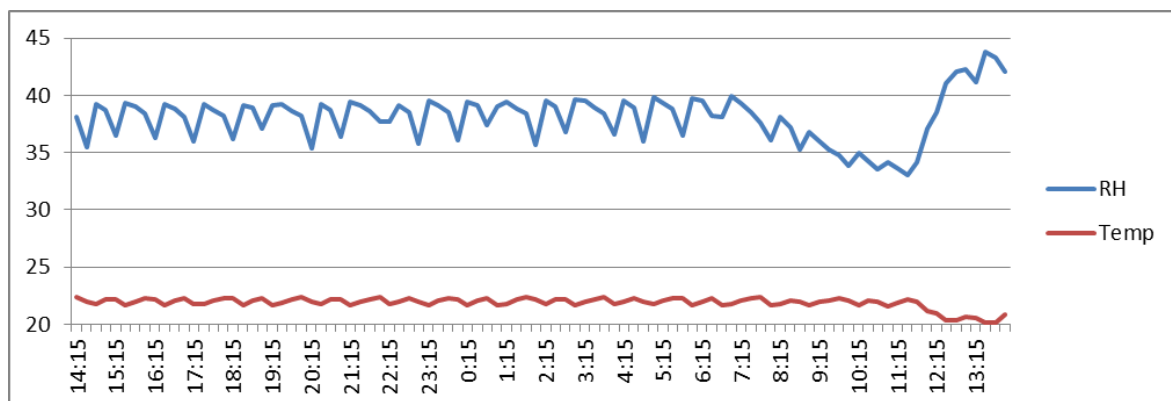


FIGURE 4. Measurements of 18 – 19 of November

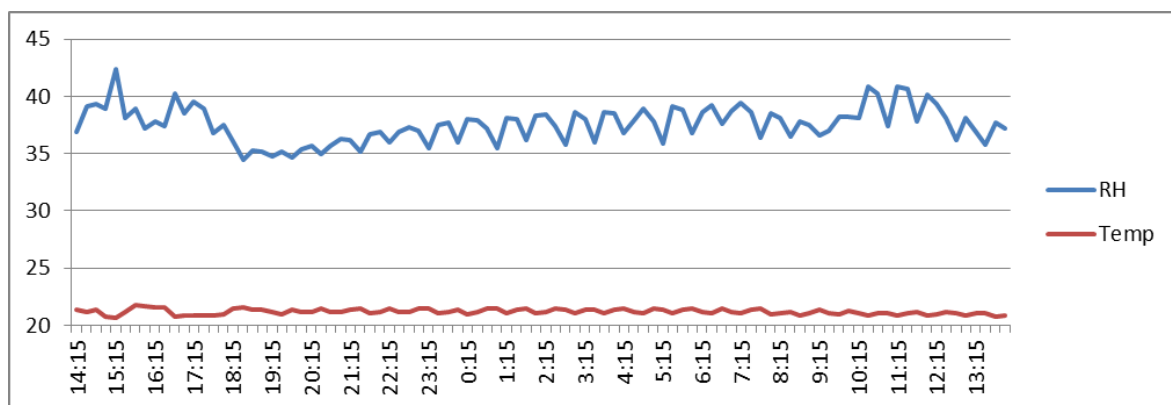


FIGURE 5. Measurements of 19 – 20 of November

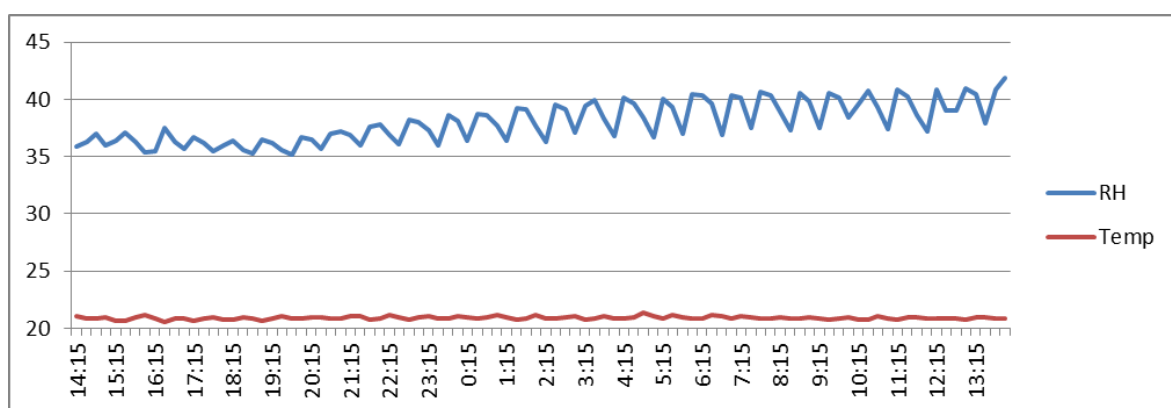


FIGURE 6. Measurements of 20 – 21 of November

APPENDIX 21(1)

Data Logger #16

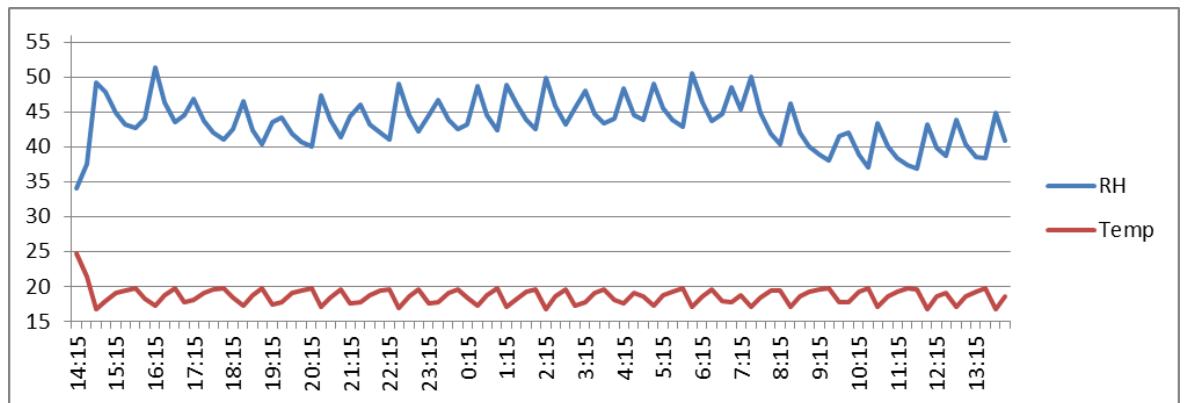


FIGURE 1. Measurements of 15 – 16 of November

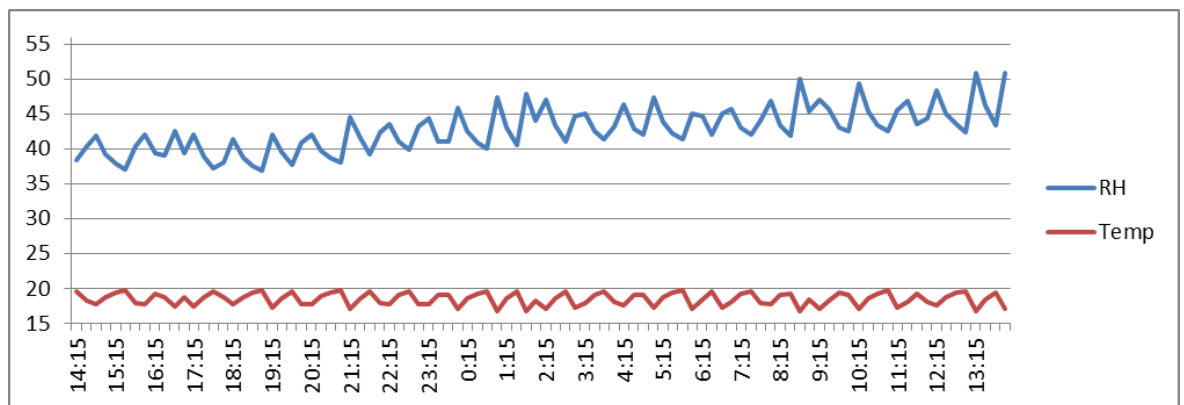


FIGURE 2. Measurements of 16 – 17 of November

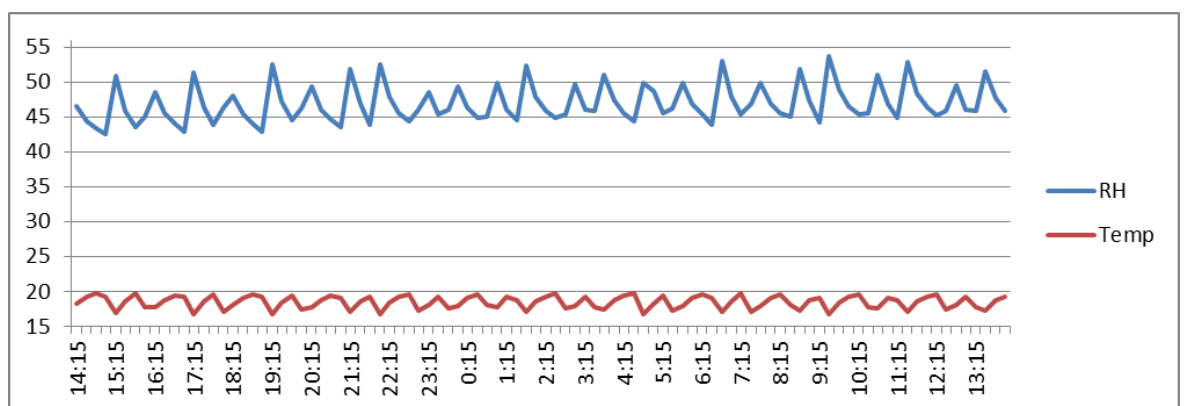


FIGURE 3. Measurements of 17 – 18 of November

APPENDIX 21(2)

Data Logger #16

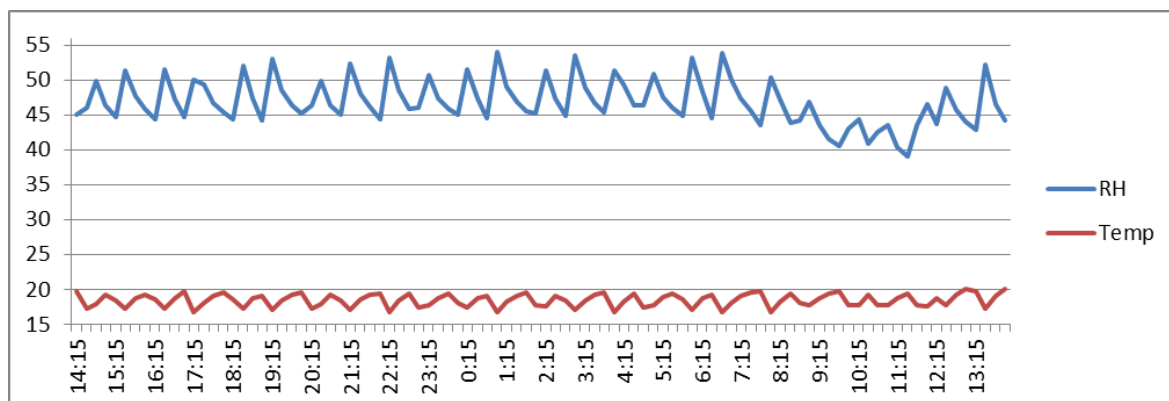


FIGURE 4. Measurements of 18 – 19 of November

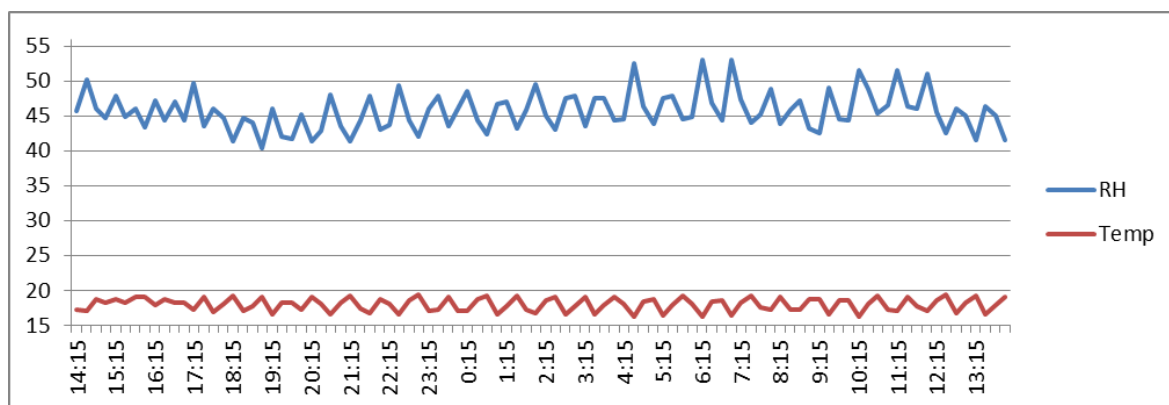


FIGURE 5. Measurements of 19 – 20 of November

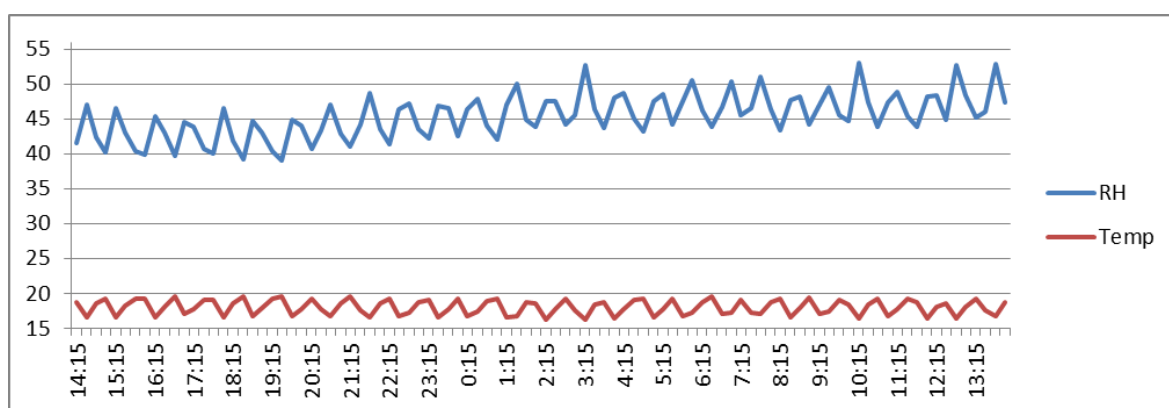


FIGURE 6. Measurements of 20 – 21 of November

APPENDIX 22(1)

Location #4, 19-20 of November

Temperature change rate for 19-20 of November

Sampling period		t _{max}	t _{min}	Δt	Sampling period		t _{max}	t _{min}	Δt
14:15	15:15	15,8	12,0	3,8	1:45	2:45	15,5	11,2	4,3
14:30	15:30	15,8	12,5	3,3	2:00	3:00	15,5	11,2	4,3
14:45	15:45	15,8	12,5	3,3	2:15	3:15	15,5	11,2	4,3
15:00	16:00	15,7	12,5	3,2	2:30	3:30	15,2	11,2	4,0
15:15	16:15	15,7	12,5	3,2	2:45	3:45	15,2	11,2	4,0
15:30	16:30	15,5	12,5	3,0	3:00	4:00	15,8	11,4	4,4
15:45	16:45	15,5	13,2	2,3	3:15	4:15	15,8	11,4	4,4
16:00	17:00	15,0	12,7	2,3	3:30	4:30	15,8	11,4	4,4
16:15	17:15	15,0	12,7	2,3	3:45	4:45	15,8	12,2	3,6
16:30	17:30	15,4	12,7	2,7	4:00	5:00	15,8	12,2	3,6
16:45	17:45	15,4	11,5	3,9	4:15	5:15	15,8	11,2	4,6
17:00	18:00	15,4	11,5	3,9	4:30	5:30	15,8	11,2	4,6
17:15	18:15	16,0	11,5	4,5	4:45	5:45	15,9	11,2	4,7
17:30	18:30	16,0	11,5	4,5	5:00	6:00	15,9	11,2	4,7
17:45	18:45	16,0	11,5	4,5	5:15	6:15	15,9	11,2	4,7
18:00	19:00	16,0	11,5	4,5	5:30	6:30	15,9	12,4	3,5
18:15	19:15	16,0	11,5	4,5	5:45	6:45	15,9	12,4	3,5
18:30	19:30	15,3	11,5	3,8	6:00	7:00	15,8	12,2	3,6
18:45	19:45	15,3	11,8	3,5	6:15	7:15	15,8	12,2	3,6
19:00	20:00	15,3	11,8	3,5	6:30	7:30	15,9	12,2	3,7
19:15	20:15	16,1	11,8	4,3	6:45	7:45	15,9	12,0	3,9
19:30	20:30	16,1	12,4	3,7	7:00	8:00	15,9	12,0	3,9
19:45	20:45	16,1	12,4	3,7	7:15	8:15	16,1	12,0	4,1
20:00	21:00	16,1	12,4	3,7	7:30	8:30	16,1	11,9	4,2
20:15	21:15	16,1	12,4	3,7	7:45	8:45	16,1	11,9	4,2
20:30	21:30	16,0	11,9	4,1	8:00	9:00	16,1	11,9	4,2
20:45	21:45	16,0	11,9	4,1	8:15	9:15	16,1	11,9	4,2
21:00	22:00	16,0	11,9	4,1	8:30	9:30	15,7	11,9	3,8
21:15	22:15	16,0	11,9	4,1	8:45	9:45	15,9	12,5	3,4
21:30	22:30	16,0	11,9	4,1	9:00	10:00	15,9	12,5	3,4
21:45	22:45	16,0	12,6	3,4	9:15	10:15	15,9	11,5	4,4
22:00	23:00	16,0	12,6	3,4	9:30	10:30	15,9	11,5	4,4
22:15	23:15	16,0	11,6	4,4	9:45	10:45	15,9	11,5	4,4
22:30	23:30	16,0	11,6	4,4	10:00	11:00	15,9	11,5	4,4
22:45	23:45	16,2	11,6	4,6	10:15	11:15	15,9	11,5	4,4
23:00	0:00	16,2	11,6	4,6	10:30	11:30	16,1	11,8	4,3
23:15	0:15	16,2	11,6	4,6	10:45	11:45	16,1	11,8	4,3
23:30	0:30	16,2	11,6	4,6	11:00	12:00	16,1	11,8	4,3
23:45	0:45	16,2	11,6	4,6	11:15	12:15	16,1	12,2	3,9
0:00	1:00	15,7	11,4	4,3	11:30	12:30	16,1	12,2	3,9
0:15	1:15	15,7	11,4	4,3	11:45	12:45	15,5	11,5	4,0
0:30	1:30	16,4	11,4	5,0	12:00	13:00	15,7	11,5	4,2
0:45	1:45	16,4	11,4	5,0	12:15	13:15	15,7	11,5	4,2

APPENDIX 22(2)

Location #4, 19-20 of November

Sampling period		t _{max}	t _{min}	Δt	Sampling period		t _{max}	t _{min}	Δt
1:00	2:00	16,4	11,4	5,0	12:30	13:30	15,7	11,4	4,3
1:15	2:15	16,4	11,8	4,6	12:45	13:45	15,7	11,4	4,3
1:30	2:30	16,4	11,8	4,6	13:00	14:00	15,9	11,4	4,5

APPENDIX 23(1)

Location #4, 20-21 of November

Temperature change rate for 20-21 of November

Sampling period		t _{max}	t _{min}	Δt	Sampling period		t _{max}	t _{min}	Δt
14:15	15:15	16,0	11,6	4,4	1:45	2:45	16,1	11,2	4,9
14:30	15:30	16,0	11,6	4,4	2:00	3:00	16,0	11,2	4,8
14:45	15:45	16,0	11,6	4,4	2:15	3:15	16,0	11,2	4,8
15:00	16:00	16,0	11,6	4,4	2:30	3:30	16,0	12,1	3,9
15:15	16:15	16,0	11,4	4,6	2:45	3:45	16,0	12,1	3,9
15:30	16:30	16,0	11,4	4,6	3:00	4:00	15,8	11,4	4,4
15:45	16:45	16,0	11,4	4,6	3:15	4:15	15,8	11,4	4,4
16:00	17:00	16,0	11,4	4,6	3:30	4:30	15,9	11,4	4,5
16:15	17:15	16,0	11,4	4,6	3:45	4:45	15,9	11,4	4,5
16:30	17:30	16,0	11,6	4,4	4:00	5:00	15,9	11,4	4,5
16:45	17:45	16,0	11,6	4,4	4:15	5:15	15,9	11,5	4,4
17:00	18:00	15,8	11,6	4,2	4:30	5:30	15,9	11,5	4,4
17:15	18:15	15,8	12,2	3,6	4:45	5:45	15,3	11,5	3,8
17:30	18:30	15,8	12,2	3,6	5:00	6:00	15,3	11,5	3,8
17:45	18:45	15,8	11,5	4,3	5:15	6:15	15,8	11,5	4,3
18:00	19:00	15,8	11,5	4,3	5:30	6:30	15,9	11,5	4,4
18:15	19:15	16,0	11,5	4,5	5:45	6:45	15,9	11,5	4,4
18:30	19:30	16,0	11,5	4,5	6:00	7:00	15,9	11,8	4,1
18:45	19:45	16,0	11,5	4,5	6:15	7:15	16,3	11,8	4,5
19:00	20:00	16,0	11,5	4,5	6:30	7:30	16,3	11,8	4,5
19:15	20:15	16,4	11,5	4,9	6:45	7:45	16,3	11,8	4,5
19:30	20:30	16,4	11,5	4,9	7:00	8:00	16,3	12,0	4,3
19:45	20:45	16,4	11,5	4,9	7:15	8:15	16,3	12,0	4,3
20:00	21:00	16,4	12,2	4,2	7:30	8:30	15,7	11,5	4,2
20:15	21:15	16,4	12,2	4,2	7:45	8:45	15,7	11,5	4,2
20:30	21:30	16,1	12,1	4,0	8:00	9:00	16,5	11,5	5,0
20:45	21:45	16,1	12,1	4,0	8:15	9:15	16,5	11,5	5,0
21:00	22:00	16,1	12,1	4,0	8:30	9:30	16,5	11,5	5,0
21:15	22:15	16,1	12,1	4,0	8:45	9:45	16,5	11,9	4,6
21:30	22:30	16,0	11,5	4,5	9:00	10:00	16,5	11,9	4,6
21:45	22:45	16,0	11,5	4,5	9:15	10:15	15,9	11,9	4,0
22:00	23:00	16,0	11,5	4,5	9:30	10:30	15,9	12,2	3,7
22:15	23:15	15,8	11,5	4,3	9:45	10:45	15,9	12,2	3,7
22:30	23:30	15,8	11,4	4,4	10:00	11:00	15,8	11,5	4,3
22:45	23:45	15,8	11,4	4,4	10:15	11:15	15,8	11,5	4,3
23:00	0:00	15,8	11,4	4,4	10:30	11:30	16,0	11,5	4,5
23:15	0:15	15,8	11,4	4,4	10:45	11:45	16,0	11,5	4,5
23:30	0:30	15,8	11,4	4,4	11:00	12:00	16,0	11,4	4,6
23:45	0:45	15,8	11,6	4,2	11:15	12:15	16,0	11,4	4,6
0:00	1:00	15,8	11,6	4,2	11:30	12:30	16,0	11,4	4,6
0:15	1:15	15,8	11,5	4,3	11:45	12:45	15,7	11,4	4,3
0:30	1:30	15,8	11,5	4,3	12:00	13:00	15,7	11,4	4,3
0:45	1:45	16,1	11,5	4,6	12:15	13:15	16,0	11,9	4,1

APPENDIX 23(2)

Location #4, 20-21 of November

Sampling period		t_{\max}	t_{\min}	Δt	Sampling period		t_{\max}	t_{\min}	Δt
1:00	2:00	16,1	11,5	4,6	12:30	13:30	16,0	11,9	4,1
1:15	2:15	16,1	11,2	4,9	12:45	13:45	16,0	11,9	4,1
1:30	2:30	16,1	11,2	4,9	13:00	14:00	16,1	12,1	4,0