Increasing Efficiency of Air Handling Unit in Cleanroom Air Conditioning System

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Abstract:- A clean room is an environment, primarily used in developing as well as performing scientific research having environmental contaminants such as dust, airborne microorganisms, aerosol particles, and chemical vapors are at a minimum. A clean room has a more precise level of pollution that can be explained by the number of particles of a specific size. This study focuses on the air handling unit of cleanroom air conditioning system. Various methods related to clean room air conditioning systems are reviewed along with finding the energy efficiency for recirculating air conditioning systems, calculating fan power intensity for re-circulation air systems, the air change rates and its relation with cleanroom velocities.

Keywords:- *Cleanroom, Air Conditioning System, Fan Power, Recirculation Air Systems, Energy Efficiency.*

I. INTRODUCTION

Development and control of cleanroom environment control systems are very important for energy efficiency. These have an interrelation concerning environmental control performance as well as energy performance. Only after a correctly designed air-conditioning system can any adequate control be installed. The control engineers are responsible for considering all the elements. Particle, microbial, electrostatic discharge, molecular, and gaseous contamination control, airflow pattern control, pressurization, sound and vibration control, industrial engineering aspects, and manufacturing equipment are all important factors that good cleanroom systems control to keep installation and operating costs parallel to the ground. The concentration of airborne particles is regulated in a cleanroom, which minimizes particle introduction, creation, and retention. Cleanroom air conditioning systems have been the subject of extensive investigation.

II. LITERATURE REVIEW

Zhou et al. (2017) Particle concentration models for cleanrooms based on particle dispersion, mass airflow balancing, and indoor particle conservation were investigated. The models were assessed based on the assumptions they made, key parameters used in the study, and the applications' constraints. Apart from these, an improved model is proposed to simplify the model into numerous simpler equations, demonstrating its suitability for building cleanroom air supply systems and energy coefficients.In (Bannister, 2008) the main control methodologies for VAV systems are represented in terms of energy efficiency, robustness, and long term manageability. The main control issues include fan control, supply air temperature control, VAV termination control, and coordination of terminal and AHU actions for reducing heating and cooling effect occurring simultaneously. Nowadays most of the key algorithms used in VAV system control is not properly modeled leaving most significant control optimization for the assessment using intuition instead of analysis. This study aims to incorporate certain key features of VAV control which is essential to be embedded within the simulation packages for providing the complete assessment of the air conditioning system. Tschudi et al. (2005) introduces a numerical approach and field testing investigation for improving the performance for a hospital operating room within a limited budget. The potential of this energy based strategy is verified through a variable speed is driven strategy under standards filled with pollutions. Dincer and Rosen (2015) provides a clear and concise description of exergy analysis and its many uses. Johnson (2000) shows a clean room and a chemical air filter suitable for use in the air handling system of the clean room directly upstream of high-efficiency particulate air (HEPA) filters. Kinkead et al. (1997) presented an air filtering system to chemical-filter all of the clean room supply air, the recirculated air undergoes chemical-filtering every time it is recirculated, resulting in the continued removal of gas-phase contaminants generated by processes performed in the clean room. Ghattas (2012) discussed a clean room air handling system which includes an air handler used for receiving an air flow, the air handler further furnished with a cooling apparatus, and at least one supply fan for generating the air flow without a cooling apparatus directly associated therewith, and modulation means for operating said system. Benson et al. (1991) provides a centrifugal fan which has the ability to match the rated capacity to the demands of air by the system along with avoiding the maintenance problems of the variable speed drive. Kleinsek and Kleinsek (1993) explained the air filtering ceiling system having a plurality of flow through filtering ceiling panels, where each panel is taken for fluid tight communication with adjacent ceiling panels wherein all of the air entering a plenum enters through the panels, the individual panels being further considered for snap in and out of a ceiling panel support structure. Smith et al. (1974) highlighted the role of humidification in controlled-contamination environments, where the processes contain high value, and the absence of or incorrect humidity control causes irreparable defects. The problems that may occur are discussed along with the technologies available on the market to maintain humidity in this mission-critical application. Relative humidity is found to decrease whenever the air is sensitively heated, or due to migration of moisture content as a result of different partial vaporization pressures between two adjacent rooms. These situations occur in winter, and in particular in systems with all outside air, when the incoming air, with a high relative humidity and low temperature, are heated considerably. The speed of chemical reactions also is dependent on the moisture content of the air, which therefore plays a significant role in achieving a high quality product. The moisture content of the air must needs to be controlled, for avoiding electrostatic discharges and short circuits. Controlling and maintaining relative humidity between 40% and 60% thus minimizes the proliferation and spread of bacteria and other biological contaminants. In (You et al., 1999) the Cleanroom Design Guidelines provide many successful design approaches that are applicable to most cleanroom facilities based on actual measurement of operating cleanroom facilities and input from cleanroom designers, owners and operators. No single recommendation is appropriate for every cleanroom facility, but baseline measurement possesses clearly shown large efficiency differences between design solutions supporting identical cleanroom conditions. The Design Guidelines offers recommendations to the cleanroom designer who has little time or budget for evaluating the wide range of efficiency options suitable for and proven in cleanroom facilities. Schneider (2001) discussed a clean room arrangement including a clean room consisting of an upper portion and a lower portion, clean air being introduced into the clean room from the upper portion moving downward and expelled from the lower portion. Bhatia (2012) discussed an online engineering PDH course for providing an overview of cleanroom and discusses the key HVAC design aspects applicable to cleanrooms. The idea of a cleanroom may seem to be science fiction, clean and controlled environments have been utilized by a wide range of industries. Cleanrooms provide an essential role in modern production and research from their more obvious uses in medical facilities to their necessity in integrated circuit manufacture. There are five key elements for the control of airborne particulate matter which prevents entry of particulate matter, purges of particulate matter, prohibits the generation of particulate matter, protects the product from impact and settling of particulate matter and provides an area for the cleaning of parts and personnel. Wetzel and Wetzel (1987) A clean room which can be made to be easy-to-install by making it a unit type and which can have a wide working space while exhibiting high performance air cleaning action is provided. The unit type clean room includes a machine chamber unit, a front chamber unit, and a clean room unit. The machine chamber unit includes air conditioners and constant air flow units installed therein.

Ghattas (2012) disclosed a clean room air handling system. The system including an air handler are taken to receive an air flow, the air handler further has a cooling apparatus, and at least one supply fan for generating the air flow without a cooling apparatus directly associated therewith, and modulation means for operating said system. Renz et al. (1999) discussed a blower unit for clean rooms consisting of housing with a bottom, a cover, and first and second sidewalls. A filter is attached to the bottom. At least one blower needs to be mounted in the housing. At least one air flow channel is attached to the blower and extends within the housing in an upward direction between two opposite ones of the first sidewalls. In the airflow channel clean air flows from the blower to the filter. Soundproofing material is connected to at least one side of the airflow channel. Sasaki et al. (2003) discussed an image forming apparatus as per this study represents an electrophotographic image forming apparatus forming an image onto a print medium based on input image data.

III. CLEANROOM AIR CONDITIONING

Table 1: Comparison of Airborne Particle Concentration Limits from ISO14644-1

ISO 14644 Class	**0.1µm**	**0.2µm**	**0.3µm**	**0.5µm**	**1.0µm**	**5.0µm**
	ISO 14644					
	Particle perm^3					
1	10	2				
2	100	24	10	4		
3	1000	237	102	35	8	
4	10000	2370	1020	352	83	
5	100000	23700	10200	35200	832	29
6	1000000	237000	102000	352000	8320	293

7				35200000	83200	2930
8				352000000	832000	29300
9				3520000000	8320000	293000

IV. CLEANROOM APPLICATIONS

As more and more technological advances are taking place, the use of clean space environments in developing, manufacturing, and packaging exists and the demand for cleaner workspace rises. There are various industries which use clean spaces for their products. Some of these can be summarized as follows:

- *Pharmaceuticals/Biotechnology*

The production of pharmaceutical, biological and medical products need extra clean spaces for controlling undesirable bacterial growth.

- *Microelectronics/Semiconductor*

Semiconductor microelectronics drive cleanroom design has undergone numerous advancements in recent years. In countries such as the United States, semiconductor shows an essential part of all the clean rooms out of which the latest one is ISO 14644-1 Class 5 or cleaner.

- *Aerospace*

Initially, cleanrooms were developed for aerospace applications for manufacturing and assembling satellites, missiles and aerospace electronics. Nowadays most of the applications work with large-volume spaces having cleanliness levels of ISO 14644-1 Class 8 or greener.

- *Other Applications*

Apart from the above-mentioned areas, aseptic food processing, and packaging also involve cleanrooms along with manufacturing of artificial limbs and joints, automotive paint booths, crystal, laser industries along with advanced materials research. Cleanrooms in hospitals mainly serve as an isolation room for patients along with surgery rooms where there are chances of infection.

V. IMPORTANT CONSIDERATION IN CLEAN ROOM AIR CONDITIONING

- *Air changes per hour(ACPH)*

Table 2: Air changes per hour versus vertical airflow velocities, room heights and cleanliness classes

ISO Class	**Velocity m/s**	**Air Changes per Hour for ceiling height, m**							
		2.2	15.2	18.4	24.4	30.5	36.6	42.7	48.8
2	0.43 to 0.50	128 to 150	102 to 120	85 to 100					
3	0.35 to 0.43	105 to 128	84 to 102	70 to 85	52 to 64				
4	0.30 to 0.35	90 to 105	72 to 84	60 to 70	45 to 52	36 to 42			
5	0.23 to 0.28	68 to 83	54 to 66	45 to 55	34 to 41	27 to 33	22 to 27		
6	0.12 to 0.18	38 to 53	30 to 42	25 to 35	19 to 26	15 to21	12 to 18	10 to 15	
7	0.04 to 0.08	12 to 24	10 to 19	8 to 16	6 to 12	5 to 10	4 to 8	3 to 6	3 to 2
8	0.02 to 0.03	8 to 10	5 to 7	4 to 6	3 to 4	2 to 3	2 to 3	2	2
9	0.01 to 0.015	3 to 5	2 to 3	2 to 3	2	1 to 2	1 to 2	1	1

- *Air flow pattern*

One of the challenges is airflow direction management and maintaining its control in preventing the cross-contamination of airborne particles. Although there exists various air pattern configurations, only unidirectional airflow, and non-unidirectional airflow is preferred. The efficient airflow systems minimize initial costs thus helping cleanrooms for accomplishing high performance tasks benefitting productivity.

- *Room pressurization*

Between any two rooms, the differential pressure is created at 12.5 Pa or less. The contaminants in cleanrooms are controlled by controlling the airflows between the neighboring spaces. Room airtightness builds the relationship between the room's flow offset value and the resulting pressure differential where every room airtightness shows airtightness as unique and unknown unless tested.

- *Filtration*

It is necessary to provide proper air filtration for preventing most externally generated particles from reaching the cleanroom. High efficiency air filters are of two types including high-efficiency particulate air(HEPA) filters and ultra low penetration air(ULPA) filters. Glass fiber paper technology is preferred by HEPA and ULPA filters for laminating and developing non glass media for specific applications.

- *Energy conservation in cleanrooms*

There are several operating costs related with a cleanroom including conditioning the air, fan energy for air movement in the cleanroom and process exhaust. Energy conservation is significant in cleanroom air conditioning for the intake of more air to enhance better filtration.

- *Cleanroom performance testing*

ISO 14644-3 is used for performing the validation of cleanroom. The air borne particles are used for classification and classrooms are evaluated along with testing clean air devices. Some of the tests can be included as airborne particle count for ultrafine particles, airborne particle count for micro particle, airflow test, air pressure difference test, installed filter system leakage test, airflow direction text and visualization, temperature test, humidity test, electrostatic and ion generator test, particle deposition test, recovery test, containment leak test.

VI. MEASUREMENTS AND UNCERTAINTY ANALYSIS

The clean room is created in the interior of the building using heat preservation materials such as steel panels to transfer as little heat as possible through the enclosure, according to the analysis. Thermal load, equipment, light, and other factors all contribute to the indoor cooling load. The internal heat source and the heat produced by the fan remain constant throughout the year. Similarly, the latent heat in a clean space is thought to be little due to the variance in humidity content due to the low human density. The clean room's whole cooling load is assumed to be sensible heat load. The indoor dry-build temperature, relative humidity, total cooling load for the controlled area, and design air exchange rate were all kept constant. Before and after remodeling, the total supply air rate was kept unchanged. Energy plus combines a regional heat and quantity balancing simulation with the building's HVAC system. Through reaction, the energy cost of the building in relevant weather conditions is explored, as well as a comparison of regionally regulated factors. For the same air conditioning system, the load of the cooling and heating coils revealed a similar result between the Energy Plus simulating load and the practical load for the cooling coil.

6.1. Circulation Energy Efficiency for Re-circulation Air Systems

This section will discuss the techniques involved in re-circulating the air systems required to calculate energy efficiency. Recirculation of air conditioning energy accounts for 10 to 30 % of total clean room energy usage. In conventional air conditioning system hot and humid air is combined with stale, hot and humid circulating air from the space already air conditioned. The air which is combined, undergoes cooling along with dehumidification through the cooling coil. The air at this point is very cold in nature and shows saturation for comfort. IoT is reheated electrically using either steam or hot water coils to provide design air condition before delivering as room supply air. The heat and moisture is picked up from the room and is returned back as a warmer and humid with increased intensity from the time it has entered. Similarly an equal amount of return air is recirculated and combined with incoming fresh air to the room. The cooling coil's heat is reduced via the heat exchanger. The pre coil is attached upstream and the reheat coil is attached downstream of the cooling coil in a classic recirculating run-around coil arrangement. In compared to the supply after the reheat coil, the pre cold air is found to be hotter. Heat pipes were originally developed to cool small parts for space uses. Heat pipe heat exchangers exchange a big amount of heat over a long distance with the least amount of temperature differential between the heat source and the heat sink. They aid in the recovery of waste heat from hot flue gas or cold exhaust air in air conditioning systems. By installing a heat recovery coil, it is preferable to use cold exhaust air to precool entering warm fresh outdoor air. Stationary finned or plate-type air-to-air heat exchangers or rotating heat wheels with or without desiccants are used in conventional heat recovery coils.

6.2. Fan Power Intensity for Re-circulation Air systems

This section will discuss the concept of fan power intensity and its relation with re-circulating the air systems. Specific Fan Power (SFP) is one essential parameter to quantify the energy efficiency of a fan air movement system. It is the measurement of electric power which drives fan, and is relative to the air circulated. It changes with air flow rate as well as fan pressure rise.

SPF and its operating points are expressed as follows:

$$SFP = \frac{\sum P_0}{q_0}\left[\frac{kW}{\frac{m^3}{s}}\right] \tag{1}$$

Where P_0 is the power
$\sum P_0$ is the sum of all the powers together
q_0 is the gross amount of air circulated.
q_0 denotes the largest for supply and exhaust air flow rates for unbalanced ventilation systems.
Dimensionally SFP is expressed in the following units:

$$[SFP] = \frac{kW}{\frac{m^3}{s}} = \frac{W}{\frac{l}{s}} = \frac{kJ}{m^3} = kPa \tag{2}$$

Eq. (2) showed SFP as a unit of pressure where it is measured as energy per cubic meters.

Eq. (3) stated below denotes the relationship between DFP, fan pressure rise and fan system efficiency. The SFP is found to be exactly equal to the fan pressure rise in ideal case of a lossless fan system i.e. where ρ_{tot}

$$\rho_{tot}.SFP = \Delta\eta_{tot} \tag{3}$$

Where $\Delta\eta_{tot}$ = total pressure rise of the fan, which is equivalent to the drop in total pressure through the entire ventilation system from the outdoor air and back to outside [kPa]

ρ_{tot} =the overall efficiency of the fan system [0 < ρ_{tot} < 1].
The fan system efficiency (ρ_{tot}) denotes the fraction of the electrical power that supports necessary driving pressure to transfer the air in the ventilation system.

Fan system efficiency is never constant. It falls down sharply at low flow rates due to the motor belt drive and VFD efficiencies all gets reduced gradually at low loads.

The pressure drop between two points along the flow path can be expressed as:

$$\Delta p_{ab} \approx k.u^n[Pa]$$

(4)
Where
k= constant
u= air speed [m/s]
n= exponent, a$\leq n \leq b$
(n=a for wholly laminar flow
n=b for wholly turbulent airflow)
Modern ventilation systems possess turbulent flow in the duct system and laminar flow through high-pressure loss.

6.3. Re-circulation Air Change Rates and Cleanroom Air Velocities

This section will discuss the air change rates and its relation with cleanroom velocities. The preservation of HVAC clean room quality relies heavily on air changes in the clean room. The number of total replacements of any room's air in one hour is referred to as air changes per hour. It will be counted as one air change per hour if the supply of air in one hour is equal to the volume of the room. If a room has 60 air changes per hour it indicates 60 times the air supply will be provided as compared to the volume of the room.

The four corners, as well as the center of the HEPA filter and its readings, are determined in order to calculate the air velocity in feet per minute.

$$V_{mean} = \frac{v_1 + v_2 + v_3 + v_4 + v_5}{5}$$

The area of the filter is calculated by multiplying the length and width of the filter in feet

$A = 1Xw$
l=length of HEPA filter
w=width of HEPA filter
The total air volume per minute supplied in the clean room can be calculated as follows:

$$T = A \times V_{mean}$$

A=average of HEPA filter in square feet
V_{mean}=average air velocity in feet per minute
The total air in the clean room multiplying length, width and height of the room in feet can be calculated as follows:

$$Air\ changes\ per\ hour = \frac{T \times 60}{Volume}$$

VII. DISCUSSION

This paper reviewed the overall air conditioning systems and its application in clean room. This paper gives the complete background of cleanroom air conditioning system by emphasizing on the various techniques of improving the efficiency of the air handling unit. The various works related to enhancing the efficiency of air handling unit in the cleanroom are reviewed and discussed. The complete functioning of cleanroom along with the various modes of improving the efficiency of air handling unit in cleanroom are discussed. Further various applications of a cleanroom including their costs of support, maintenance, software and security are discussed. Various energy measurements are studied to improve the efficiency of the air handling unit in the cleanroom. The concept of re-circulating the air systems required is shown for energy efficiency calculation. The concept of fan n power intensity and its relation with re-circulating the air systems is discussed. Apart from this the air change rates and its relation with cleanroom velocities are explained.

VIII. FINDINGS AND CONCLUSION

Cleanroom air cooling is more complicated and difficult to implement than comfort air conditioning. Cleanrooms built in this manner use less external air for temperature and humidity management, lowering the energy cost of maintaining a stable clean room environment.

REFERENCES

[1]. Bannister, P., 2008. Energy efficiency and the control and simulation of VAV systems. In *2008 ACEEE Summer Study on Energy Efficiency in Buildings*.
[2]. Benson, D.E. and Post, M.T., Broad and McCLung-Pace Co, 1991. *Clean room air system*. U.S. Patent 5,014,608.
[3]. Bhatia, A., 2012. HVAC Design for Cleanroom Facilities. *Continuing Education and Development, Inc.*, https://www. cedengineering. Com.
[4]. Dincer, I. and Rosen, M.A., 2015. *Exergy analysis of heating, refrigerating and air conditioning: methods and applications*. Academic Press.
[5]. Fiorita, J.L., JR., 2017. *Clean room control system and method*. U.S. Patent 9,581,347.
[6]. Fouladi, K., Wemhoff, A.P., Silva-Llanca, L., Abbasi, K. and Ortega, A., 2017. Optimization of data center

cooling efficiency using reduced order flow modeling within a flow network modeling approach. *Appl. Therm. Eng.*, *124*, 929-939. https://doi.org/10.1016/j.applthermaleng.2017.06.057

[7]. Fu-Jen Wang PhD, P.E., Chi-Ming Lai PhD, P.E., Tsung-Jung Cheng PhD, P.E. and Liu, Z.Y., 2010. Performance investigation for the cleanroom contamination control strategy in an operating room. *ASHRAE Trans.*, *116*, 74.

[8]. Ghattas, R., 2012. *Air handling system for clean room*. U.S. Patent 8,147,301.

[9]. Ghattas, R., 2012. *Air handling system for clean room*. U.S. Patent 8,147,301.

[10]. Honda, S., Abe, H. and Isono, K., Asahi Kogyosha Co Ltd, 1992. *Clean room arrangement*. U.S. Patent 5,169,418.

[11]. Jaisinghani, R.A., Jaisinghani Rajan A, 2009. *Energy efficient air handling system for cleanrooms*. U.S. Patent 7,539,601.

[12]. Jeng, M.S., Xu, T. and Lan, C.H., 2004. Toward green systems for cleanrooms: Energy efficient fan-filter units.

[13]. Johnson, R.P., SEH America Inc, 2000. *Clean room air filtering system*. U.S. Patent 6,123,617.

[14]. Kinkead, D.A., Rezuke, R.W. and Higley, J.K., Extraction Systems Inc, 1997. *Clean room air filtering*. U.S. Patent 5,626,820.

[15]. Kleinsek, D.A., Kleinsek Don A, 1993. *Clean room and clean room containment center*. U.S. Patent 5,259,812.

[16]. Lin, T., Hu, S.C. and Xu, T., 2015. Developing an innovative fan dry coil unit (FDCU) return system to improve energy efficiency of environmental control for mission critical cleanrooms. *Energy. Build.*, *90*, 94-105. DOI:10.1016/j.enbuild.2014.12.003

[17]. Luetkemeyer, D., CUSTOM CLEANROOM CONCEPTS, 1999. *Clean air system*. U.S. Patent 5,858,041.

[18]. Nagafune, H., Fukumoto, T., Shibuya, H. and Ezaki, K., Mitsubishi Electric Corp, 1998. *Clean room having an air conditioning system*. U.S. Patent 5,752,985.

[19]. Passadore, A.M., Broad and McCLung-Pace Co, 1993. *Clean room air system*. U.S. Patent 5,207,614.

[20]. Renz, M. and Bauer, H., Meissner and Wurst GmbH and Co Lufttech Anlagen Gebaude u Verfahrent, 1999. *Blower unit for clean room*. U.S. Patent 5,876,279.

[21]. Saiki, A., Suzuki, M., Sunami, H., Asai, S., Maki, M. and Asami, K., Hitachi Plant Construction Co Ltd and Hitachi Ltd, 1987. *Clean room*. U.S. Patent 4,693,173.

[22]. Sasaki, T., Kaijo, S., Yokota, S., Kamitani, M. and Honma, T., Hitachi Plant Construction Co Ltd, 2003. *Clean room device*. U.S. Patent 6,572,468.

[23]. Schneider, R.K., 2001. Designing clean room HVAC systems. *ASHRAE J.*, *43*(8), 39.

[24]. Singh, H., Vidja, J., Agrawal, M., Sharma, R.K. and Pathak, S., 2016. Execution & Qualification of Heating, Ventilation and Air Conditioning System. *J. Pharm. Res. Educ.*, *1*(1), 172-195.

[25]. Smith, T., Pond, R. and Rivers, R., American Air Filter Co Inc, 1974. *Ceiling filter system for clean room*. U.S. Patent 3,782,082.

[26]. Suzuki, M., Yamaguchi, K., Katayama, H., Muta, T., Okubo, M., Mochizuki, A. and Adachi, H., Kajima Corp, 1987. *Clean room having partially different degree of cleanliness*. U.S. Patent 4,699,640.

[27]. Tsao, J.M., Hu, S.C., Chan, D.Y.L., Hsu, R.T.C. and Lee, J.C.C., 2008. Saving energy in the make-up air unit (MAU) for semiconductor clean rooms in subtropical areas. *Energy. Build.*, *40*(8), 1387-1393. DOI:10.1016/j.enbuild.2007.12.005

[28]. Tschudi, W., Faulkner, D. and Hebert, A., 2005. Energy efficiency strategies for cleanrooms without compromising environmental conditions. *ASHRAE trans.*, *111*, 637.

[29]. Wei Sun, P.E., 2008. Cleanrooms.

[30]. Wetzel, L.E., Wetzel Lawrence E, 1987. *Clean room module*. U.S. Patent 4,667,580.

[31]. Xu, T., 2002. *Airflow design for cleanrooms and its economic implications* (No. LBNL-51549). Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States).

[32]. Xu, T., 2003. Performance evaluation of cleanroom environmental systems. *J. IEST*, *46*(1), 66-73.

[33]. Xu, T., 2004. Considerations for efficient airflow design in cleanrooms. *J. IEST*, *47*(1), 24-28. https://doi.org/10.17764/jiet.47.1.y66g4752h3882055

[34]. Yamagata, T., Uchikawa, T., Yamamoto, S., Tomikawa, S., Ogasahara, Y. and Sukagawa, M., Shimizu Construction Co Ltd, 1987. *Clean room*. U.S. Patent 4,694,736.

[35]. You, N.H., Hwang, J.S. and Han, Y.J., Samsung Electronics Co Ltd, 1999. *Air conditioning system for semiconductor clean room including a chemical filter downstream of a humidifier*. U.S. Patent 5,890,367.

[36]. Žandeckis, A., Kļaviņa, K., Dzikēvičs, M., Kirsanovs, V. and Žogla, G., 2015. Solutions for Energy Efficient and Sustainable Heating of Ventilation Air: A Review. *J. Eng. Sci. Technol. Rev.*, *8*(3), 98-111, DOI:10.25103/jestr.083.14

[37]. Zhou, L., Sun, W., Huang, C., Li, H., Zou, Z. and Wu, C., 2017. Studies on Comparison of Particle Concentration Models for Cleanroom. *Procedia. Eng.*, *205*, 3308-3315. DOI:10.1016/j.proeng.2017.10.343