EXECUTIVE SUMMARY

Since the 1980’s, tuberculosis (TB) has re-emerged as a major cause of death globally. This is primarily due to the emergence of drug resistant strains of the disease. TB is an infectious disease primarily transmitted through the air. The bacterium involved, Mycobacterium tuberculosis, becomes aerosolized in small droplets of water or bodily fluid when an infected person coughs, sneezes or laughs. Many of these droplets dry into droplet nuclei, and becoming airborne following room air currents, and cause infection when they are inhaled. While the lungs are primarily affected by the disease, other affected organs include the brain, bones, kidneys and lymph nodes. A group particularly susceptible to infection are those with weakened immune systems, most notable people suffering from Human Immunodeficiency Virus (HIV), the virus which causes Acquired Immunodeficiency Syndrome (AIDS).

Individuals who are at greatest risk are those in close contact with infected people, such as healthcare workers. Others at risk include:

- Homeless people. Homeless shelters are particularly likely to need TB control measures.
- Nursing home residents.
- Intravenous drug users.
- Diabetics or cancer sufferers.
- HIV/ AIDS sufferers.
- Anybody breathing air in a confined space with an infected person, such as family members or caregivers.

As drug resistant forms of TB are extremely expensive to treat (the cost can run up to $125,000), preventative measures are a more realistic option. There are several techniques that can be utilized in healthcare facilities to provide control of the spread of the disease:

- Negative pressurization of the isolation room relative to the rest of a healthcare facility. This only acts as a means to prevent spread however: it does not remove infectious particles from the area of an infected person.
- High efficiency particulate air (HEPA) filters are used in air ducts to disinfect the air, especially if the ventilation system recirculates the air in a room, rather than providing fresh air. However, proper installation, maintenance and monitoring of the HEPA filters is essential.
- High ventilation rates, in terms of high values of air changes per hour (ACH), which control the particles by removal through ventilation. Current Center for Disease Control and Prevention (CDC) guidelines indicate that a value of 12 ACH is necessary for new facilities, while 6 ACH is the absolute minimum. The problem with this means of control is that increasing the ventilation rate results in diminishing returns in terms of removal.

- Upper room Ultraviolet Germicidal Irradiation (UVGI) is frequently used to supplement minimum ACH in both isolation rooms and other types of spaces where individuals with undiagnosed cases of TB may be present. The lamps providing radiation are located relatively high up in the room to prevent exposure to occupants.

The latter option is increasingly seen as a cost effective measure to supplement the general ventilation system in a room. However, a combination of the general ventilation system and UV lamps may not necessarily be implemented correctly within a room. For example, if the ventilation rate is high, then the particles may not spend enough time within the UV zone. Further, if the ventilation system does not provide good mixing within the room, the particles may not be transported into the UV zone.

This study is therefore intended as a means of determining the most effective use of UVGI, as well as determining ventilation system configurations, which will provide higher removal effectiveness. To do this, the airflow pattern needs to be fully understood and well organized, with important parameters being studied, such as:

- Ventilation flow rate
- Locations of air supplies/exhausts
- Supply air temperature
- Location of the UVGI
- Room configuration

Previous research has been almost entirely based on empirical methods (Chang et al. (1985), Macher et al. (1992), Vortimer et al. (1995)), which are time consuming and are limited by the cost of modifying physical installations of the ventilation systems. It also demonstrated the limitations imposed by absence of U-V treatment systems. The design guidance for isolation rooms basically relied on gross simplifications without fully understanding the effect of the complex interaction of room airflow and U-V treatment systems.

In this study, Computational Fluid Dynamics, CFD, (sometimes known as airflow modelling) has been employed. CFD has been proven to be very powerful and efficient in research projects involving parametric study on room airflow and contaminant dispersion (Jiang et al. (1997), Jiang et al.(1995), Haghighat et al. (1994) and Anderson et al. (1984)). The output of the CFD simulations can be used to examine field distributions, as well as provide overviews on the effects of parameters involved. CFD is employed as a main approach in this study. Further, an algorithm was developed in this study which allowed the particles to be tracked through the room studied, and allowed the UV dosage to be calculated for the particle. From this data, information such as the number of particles vented by the ventilation system, the number of particles killed by UV, and the number of viable particles in the room at any time could be established.

In this study, airflow modeling was used to evaluate the effects of following parameters on minimizing the risk from airborne organism in isolation rooms:

- Ventilation flow rate
- Supply temperature and external ambient condition
- Exhaust location
- Baseboard heating (in winter scenarios)
- Pressurization of the room relative to the external rooms
- Location and intensity of UV lamps in the room

Forty different cases of room configuration were considered in this study, with three different combinations of lamp location and intensity combinations. There is very little literature to suggest what is an appropriate level of deposition of particles on surfaces in an isolation room setting. However, general consciences among experts suggest that the particle deposition is extremely low. For the purpose of this research, deposition of particles on surfaces was neglected.

An assessment was made on the effectiveness of:

- The removal of bacteria via the ventilation system, through exhaust grilles, and
- Killing bacteria with UVGI.

In its totality, this document is intended to provide an architectural / engineering tool for good design practice that is generally applicable to conventional isolation room use.

The key conclusions from the research are:

- The number of particles vented out of the room increases with ACH. The variation with ACH is more pronounced for winter cases with no baseboard heating than summer cases. This is demonstrated in Figure 0.1 and 0.2.

- Cases with high exhaust grilles vent out more particles than low exhaust grille systems for the particle release points considered in this study for the low to medium ACH values considered. This trend is not present at the higher values of ACH considered.

- The results show that there is little advantage in increasing the ventilation rate in the room beyond 6 ACH for summer cases, or winter cases with baseboard heating in terms of increasing the effectiveness of the UVGI. This value is also consistent with the results of a concurrent study done by Memarzadeh and Manning (2000) examining thermal comfort and uniformity in patient rooms. In particular, this study suggests that the optimum ventilation rate for similar winter conditions considered in this study is 6 ACH to provide good levels of thermal comfort and uniformity. This value is also suitable for summer condition cases. This can be clearly seen in Figures 0.3 and 0.4.

- The number of viable particles in the room is generally lower for high exhaust grille system compared with low exhaust grille system cases for the low to medium ACH values considered.

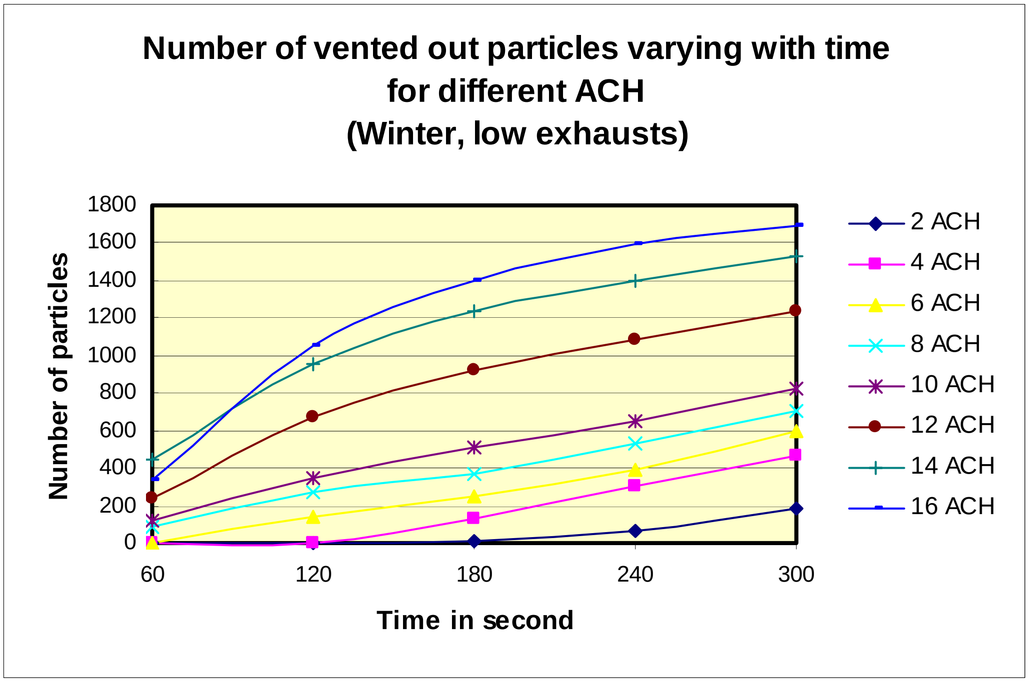


Figure 0.1. *Number of vented out particles with ACH change (Winter)*

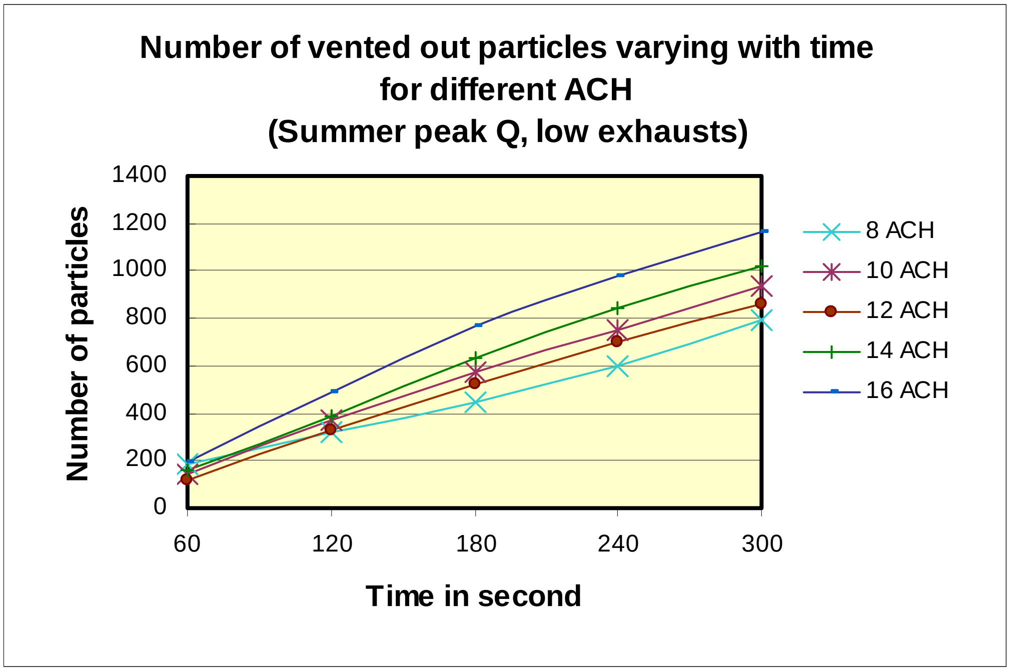


Figure 0.2. *Number of vented out particles with ACH change (Summer)*

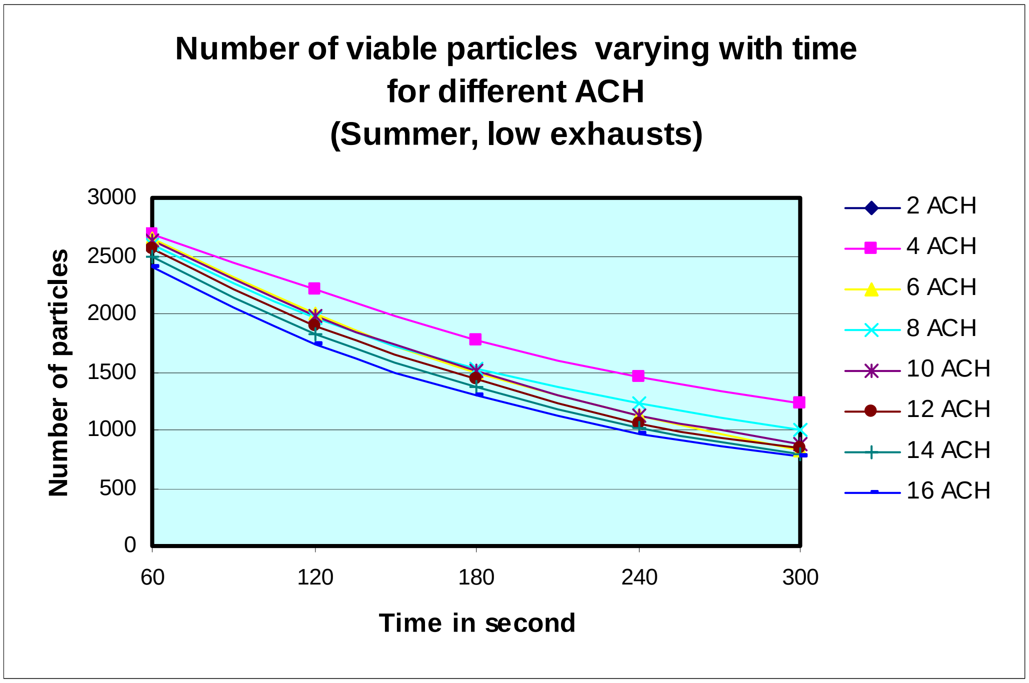


Figure 0.3. *Number of viable particles with ACH change (Summer, peak T).*

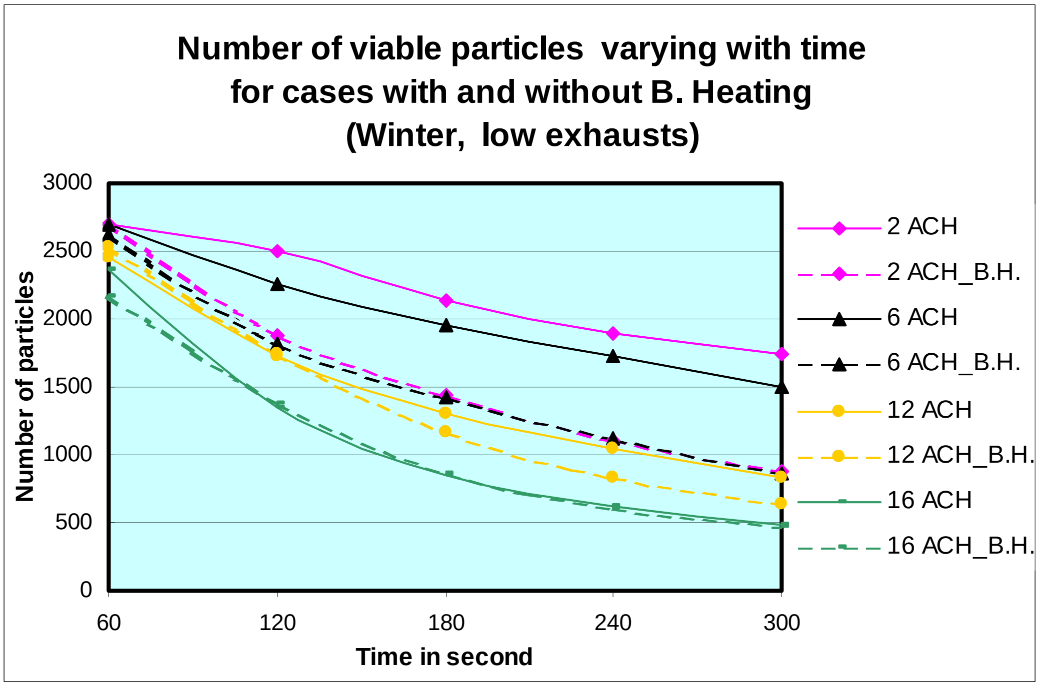


Figure 0.4*.* *Number of viable particles with /without Baseboard Heating*

- For the effectiveness of UVGI, the best ventilation rates seem to fall in the range of 10-12 ACH for winter (no baseboard heating) and at 6ACH for summer with the UVGI location being studied. This is demonstrated in Figures 0.5 and 0.6.

- UVGI does result in the killing of a significant percentage of the viable particles in the room.

- Changing the location of the UV lamp and increasing its intensity result in a higher percentage of particles being killed. However, further increases in UV intensity show diminishing returns. This is demonstrated in Figures 0.7 to 0.9.

- The addition of baseboard heating results in better kill UVGI rates irrespective of ACH. Baseboard heating should therefore be used in winter cases, especially at low ACH.

- The winter plots show that there is an increase, then a reduction in the number of killed particles by increasing ACH. For the summer case, there is a general reduction in the number of killed particles on increasing ACH. The reason for this is that, as the ACH is increased and mixing is improved, the particles dwell less time in the UV zone.

- The addition of UVGI offers a clear advantage over increasing the ACH in the ventilation system. For example, for the UV1 case, an increase from 6 to 16 ACH results in a drop of 30% in the viable particle total if UVGI was not present for summer cases. However, the introduction of UVGI results in a reduction of 68% in the number of viable particles at 6 ACH. At current costs, the inclusion of UVGI is also considerably cheaper ($1742 compared with $9000 over a ten year period for a 200 ft^2 room).

- The reduction in the number of viable particles on doubling the UV intensity for summer cases and winter cases with baseboard heating at 6 ACH is around 20%. This indicates that increasing the UV intensity is not necessarily cost effective. At current costs, this would mean an increase of $1615 ($4844 for the UV3 system compared with $3229 for the UV2 system over a ten year period for a 200 ft^2 room), the majority of which is associated with installation, not running costs.

While the emphasis here has been on the use of UV, if UV was not included, some of the conclusions listed above are still applicable. The reason for this is that the heat dissipated from the UV lamp is not significant, enough to affect the airflow pattern. In particular:

- Baseboard heating should be used in winter cases to improve mixing in the room. This reduces the influence of ACH.

- High level exhausts are generally better than low level exhausts in terms of vented percentage for the particle release points considered in this study, particularly at low to medium ACH. This trend is not present at the higher values of ACH. However, note that patient rooms display better air conditions for low exhausts at low to medium ACH, as demonstrated by Memarzadeh and Manning (2000).

Further, it should be noted that, although this study looks specifically at isolation rooms, the principles could be applied to other areas within a health care facility where infection from TB is a possibility, such as waiting rooms, diagnostic rooms and toilets.

Based on the above, the following design recommendations are made:

1/ Baseboard heating is included in winter scenarios. The addition of baseboard heating is roughly equivalent to an increase of 6 ACH.

2/ UVGI offers significant advantages in terms of reducing the number of viable particles, and should be included.

3/ It is recommended that a value of 6 ACH be utilized as a ventilation rate for extreme summer conditions, and winter conditions with baseboard heating. There are three reasons for this recommendation:

i/ Above 6 ACH, the number of particles killed by UVGI is not increased significantly except for very high values of ACH.
ii/ The cost of each additional ACH is very expensive at current costs, in particular, around \$90 per year per ACH for a single 1800ft^3 room. For the same figure of \$90 per year, an extremely efficient UVGI lamp can be located in the room. (Per assumptions in Section V)
iii/ The value of 6 ACH is also sufficient to provide good thermal comfort and uniformity in the room.

4/ Doubling the UV intensity only results in a further 20% reduction in the number of viable particles, and is expensive in terms of the initial outlay of equipment. From this viewpoint, expensive UV systems are not that cost effective, and the current recommendation of 30W per 200 ft^2 (First et. al Part II (1999)), which represents the UV1 location scenario in this study, is adequate.

5/ The UV lamp should be located 7.5’ above floor level. No clear conclusion can be drawn as to its location in the room because of the cases considered. However, the placement of the UV lamp immediately above the bed is reasonable so that it is directly out of eye contact with the patient.

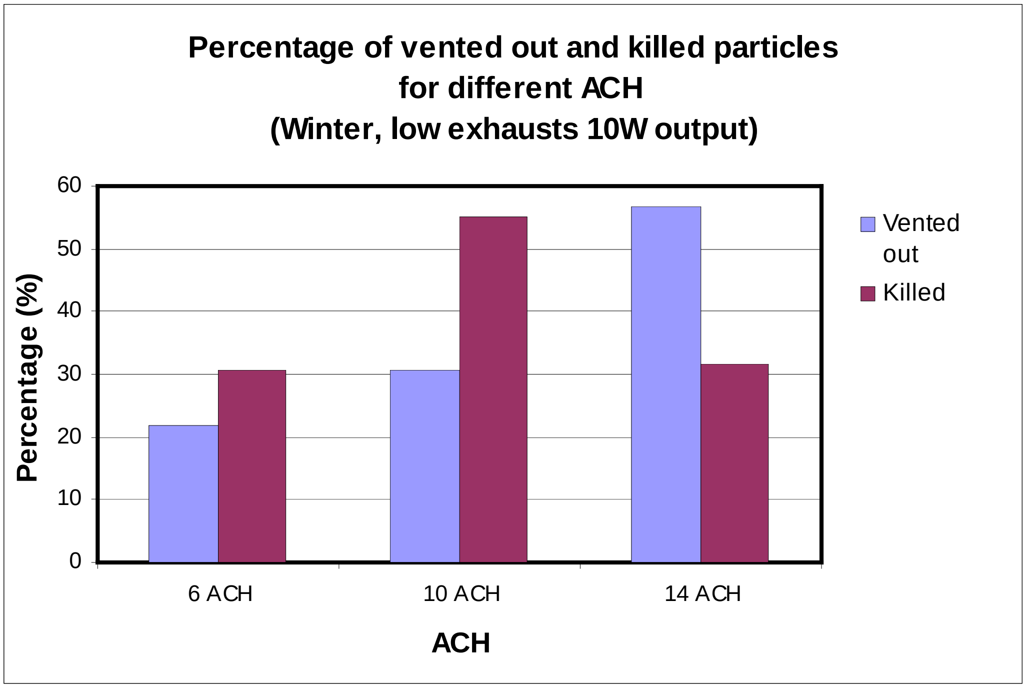


Figure 0.5. Comparison of killed and vented particles at 300s for winter condition

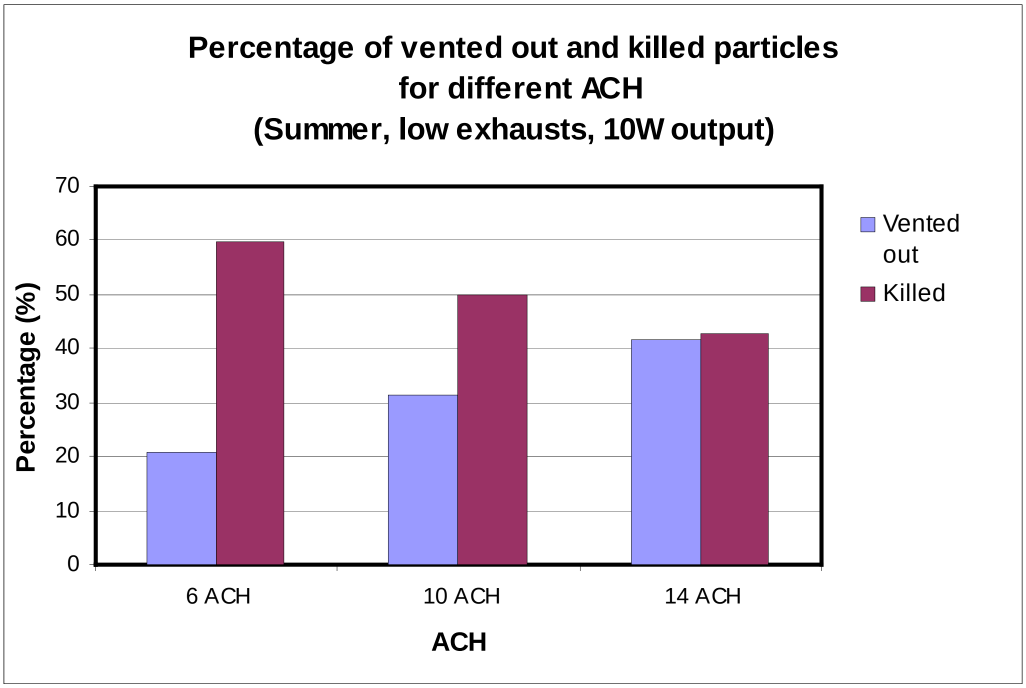


Figure 0.6. Comparison of killed and vented particles at 300s for summer condition

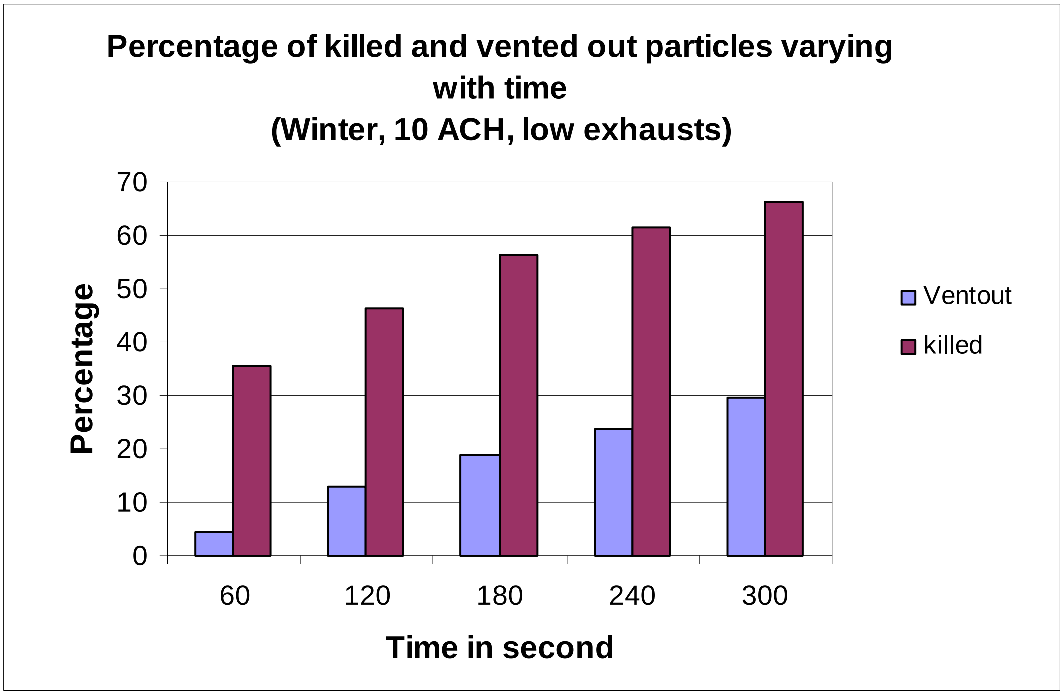


Figure 0.7. *Killed/ vented particle percentages: 10W UV output*

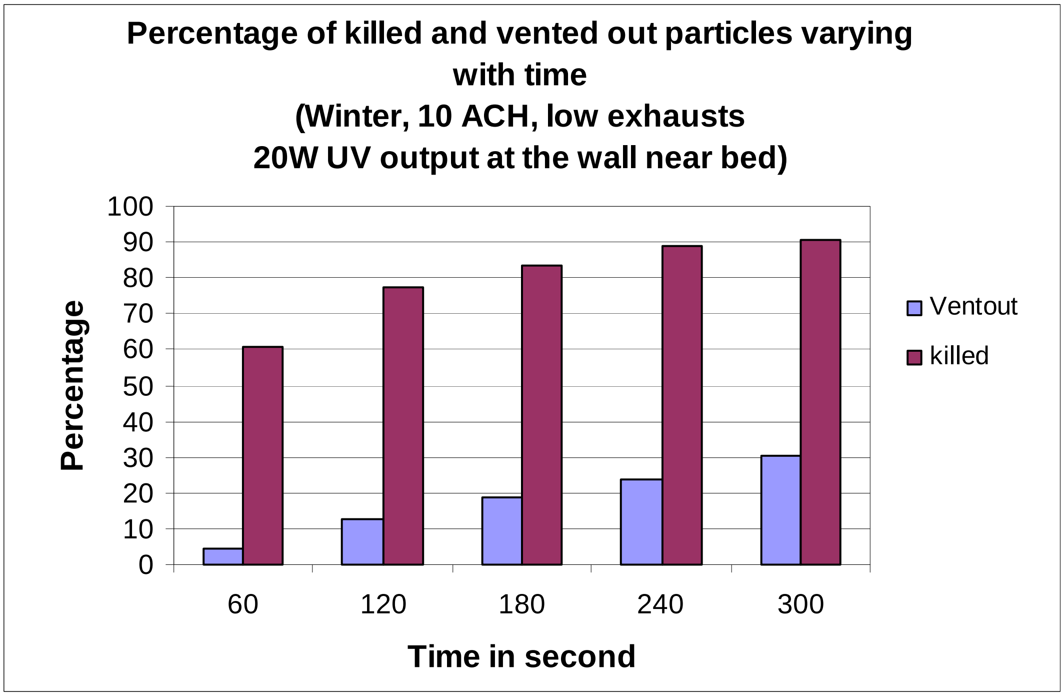


Figure 0.8. *Killed/ vented particle percentages: 20W UV output*

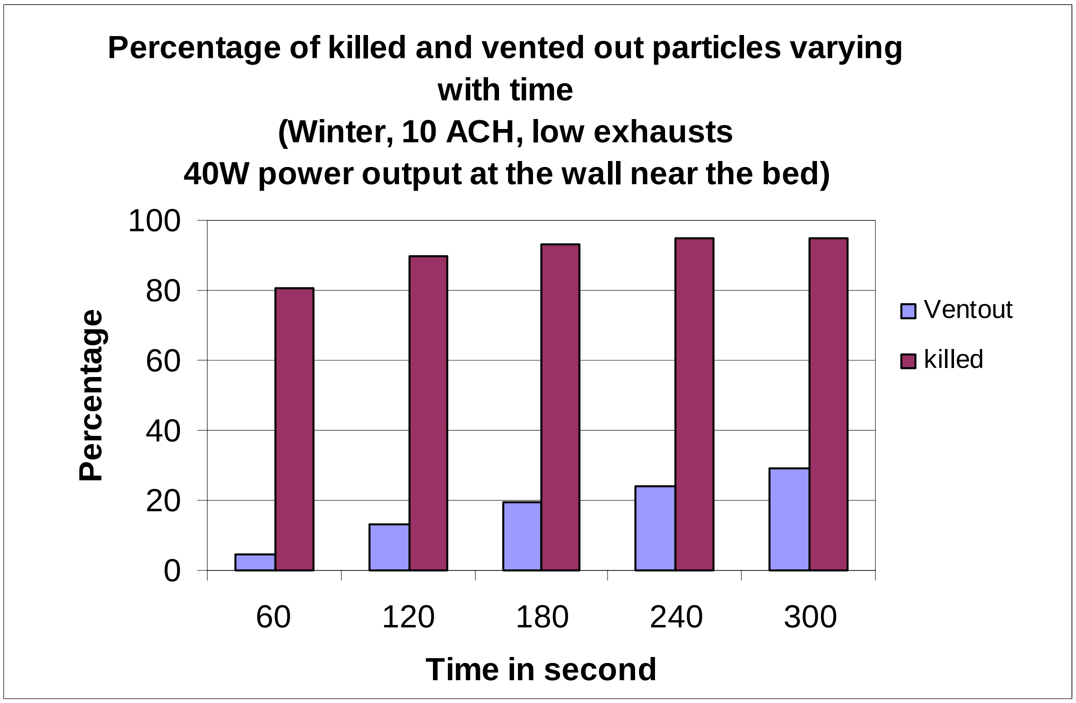


Figure 0.9. *Killed/ vented particle percentages: 40W UV output*

ACKNOWLEDGEMENTS

I wish to express my special thanks to Dr. Melvin First of Harvard University School of Public Health, for his generous assistance in reviewing this document, and providing advice and assistance throughout the development of the project.

I would also like to express my utmost appreciation and gratitude to the following members of my team for their strong support: Dr. Andrew Manning, Dr. Zheng Jiang, and Mark Seymour of Flomerics Ltd.

Also, I am grateful to everyone who participated in progress meetings for their valuable input.

Farhad Memarzadeh
Principal Investigator

TABLE OF CONTENTS

FOREWORD

Upper room UVGI holds promise of greatly lowering the concentration of airborne bacteria in a hospital isolation room. As it is designed to kill bacteria that enter the upper irradiated zone, the efficiency of the UVGI is highly reliant on vertical room air currents. An isolation room should be equipped with ventilation system that provides flow pattern not only with balanced thermal comfort and air quality, but also ensures bacteria to stay in the UV zone sufficient time to be killed.

In this project, a systematic study on minimizing the risk from airborne organisms in hospital isolation rooms with the important parameters, as listed below, was conducted.

- Ventilation flow rate
- Locations of air supplies/exhausts
- Supply air temperature and external temperature
- Location of the UV fixture(s)
- The power of the UV output

The study proved that increasing ventilation rate does not necessarily guarantee effective control of the spread of airborne infection, and that the design guidance for isolation rooms should rely on fully understanding the effect of the complex interaction of room airflow and U-V treatment systems.

Why You Should Read and Refer to This Document

Current CDC guidelines indicate that a ventilation rate of 12 ACH is recommended for new isolation room facilities, and 6 ACH for the ones already built. Recent studies, however, indicate that the thermal comfort of the patient can be severely compromised through an inappropriate ventilation system (Memarzadeh and Manning (2000)). Further, these values of ACH do not guarantee that the ventilation system will effectively remove TB particles from the room through venting, nor do they guarantee that the particles will be delivered to UV zones effectively.

This document is intended to provide valuable information to aid the design of isolation room ventilation system in conjunction with UV lamps, so that the maximum number of particles are killed or removed as quickly as possible. As the heat dissipated by the lamps themselves is small, and can effectively be ignored from the calculations, the document also offers guidelines for the most appropriate ventilation system and flow rate when no UVGI is present.

How To Use This Document

This document describes the isolation room project and its findings. The various appendices at the end of the document present relevant summary data and comparisons of parameters considered.

The document is divided into nine major sections:

1. Introduction	6. Summary
2. Purpose of the Study	7. Glossary of Terms
3. Numerical Methodology	8. References
4. Model Set-Up	
5. Results	

Section I:
Provides background information that will aid the understanding of the project. This should be read by all.

Section II:
Provides outline of objectives of project.

Section III:
Provides an explanation of the methodology used. It provides a basis for those with no knowledge of computational fluid dynamics (CFD) or particle tracking techniques. It includes description of Navier-Stokes equations, Lagrangian particle tracking equations and boundary condition used in this project. It also includes the results of particle tracking tests used to establish the validity of the approach, and outlines the application of the UV field to the room, and the description of the locations and intensities of the lamps. Finally, the bacteria killing methodology is outlined.

Section IV:
Outlines the CFD baseline model, including such details as the physical geometry chosen, the weather conditions considered, and an explanation of the ventilation system. The section also includes a table summarizing the description of 40 isolation room configurations considered in this project.

Section V:
Provides a description of the results presentation, notes on how the different totals were counted, as well as the analysis results.

Section VI

Provides a summary of the results from the project, including recommendations with regards to ventilation rate and UV location.

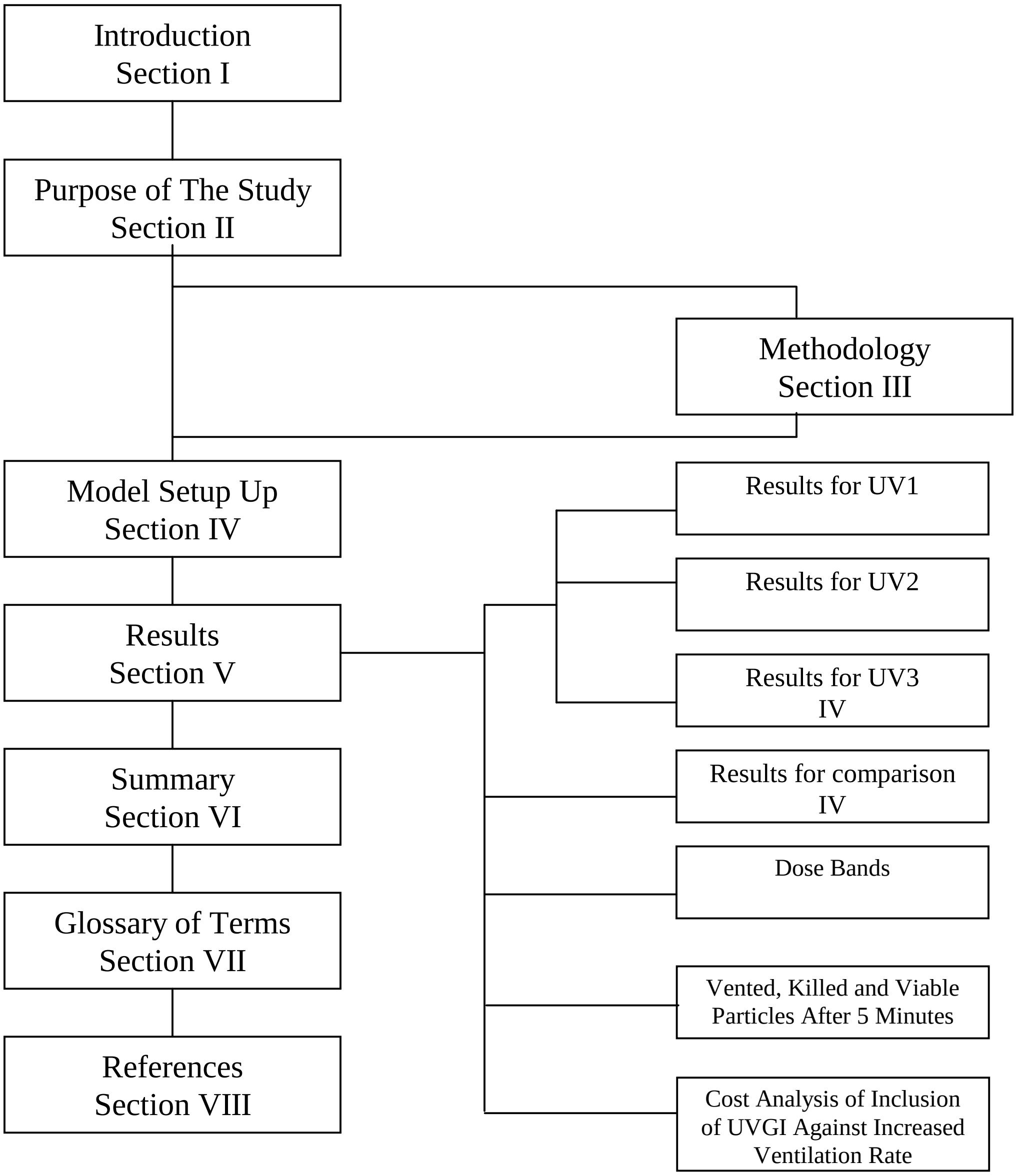
Section VII

Glossary of terms

Section VIII

Complete list of references.

Road Map for Book



SECTION I

INTRODUCTION

SECTION I: TABLE OF CONTENTS

1. INTRODUCTION

1.1 Brief Overview of Tuberculosis

Patients in hospital isolation rooms constantly produce transmissible airborne organisms by coughing, sneezing or speaking. These actions, if not under control, commonly result in spreading airborne infection.

Tuberculosis (TB) infection occurs after inhalation of a sufficient number of bacteria-carrying air droplets that are expelled during coughing, sneezing, laughing or even talking by an infected person (Federal Register (1993)). TB is a chronic or acute bacterial infection that primarily attacks the lungs, but which may also affect the kidneys, bones, lymph nodes, and brain. When particles of this infection are inhaled, bacteria lodge in the lungs and multiply. Symptoms include coughing, chest pain, shortness of breath, loss of appetite, weight loss, fever, chills, and fatigue. The elderly, children and people with weakened immune systems, including AIDS, cancer and diabetes sufferers, are most susceptible to the disease.

In the mid-1800s, tuberculosis was considered a disease that affected mainly the upper class society. However, as the epidemic continued and claimed a larger and larger circle of people, often the poor and disadvantaged, the victims themselves were often blamed for contracting the infection. The development of effective antibiotics during from the 1940s to the 1960s led the medical establishment to believe that the disease had been eradicated. During the early 1980s the number of cases began to increase and new strains of drug-resistant TB emerged. Since TB is an airborne disease, public concern was high and pressure was placed on Congress and the medical establishment to solve the problem. Funding for TB research at the National Institute of Health increased tenfold between 1991 and 1995 from $3.5 million to $35 million.

In 1996, the United States enjoyed its fourth consecutive year of declining TB case rates with just over 21,000 recorded cases, the lowest number since 1985. However, by 1996 the rate had stayed the same or actually increased in 23 states relative to 1995 (Centers for Disease Control and Prevention (US), 1997) and the incidence of multi-drug resistant TB were rising at an alarming rate.

Globally, TB is the most infectious disease, accounting for approximately three million deaths in 1995 (Raviglione (1997)), with one third of the global population believed to be infected with Mycobacterium Tuberculosis. Further, it is responsible for a total of one-fourth of all preventable deaths among adults in the rest of the world, and is the leading cause of death among people with AIDS.

Contamination depends on a number of things, including principally the rate at which bacilli are discharged and the number of bacilli released from the infectious source. Other factors include the virulence of the bacilli and more external factors, such as the ventilation flow rate in the space. Finally, the potency of airborne bacteria has a significant effect on the contamination level. Primary TB, for example, does not have noticeable symptoms and is not, in its early stages, contagious. During this spell, immune cells form a protective wall between inactive bacteria and the surrounding organs. As long as the immune system remains strong, the TB bacteria can remain dormant for many years. If the immune system becomes weakened by HIV infection, malnutrition, aging, or other factors, the infection may develop into secondary TB. In secondary TB, the formerly dormant bacteria break through the protective wall, destroy tissue in the lungs, and may invade the rest of the body via the bloodstream. At this stage, carriers of TB may begin to infect other individuals.

The past few years have seen remarkable productivity in the development of understanding of transmissible airborne diseases such as tuberculosis. Active discussions are underway within research communities regarding how best to design clinical trials of the most promising potential testing, isolation, and vaccination procedures. The challenge in the near future includes furthering basic comprehension of the human host response to mycobacterium tuberculosis while applying this knowledge to rational candidates and planning out the future of removing this threat to human health.

1.2 Control of Tuberculosis in Populated Buildings

The solutions available to current health care providers are often considered inadequate and expensive, since most involve extensive research, drug therapy, and costly vaccines. Treating a patient infected with a drug-resistant form of TB can cost as much as $125,000. A much better tool for fighting airborne diseases is the long-term control and elimination of the infection as a threat in the United States and the rest of the world.

In order to prevent the transmission of airborne infections patients with diagnosed TB are generally placed in isolation rooms equipped with high efficiency ventilation systems operating at high supply flow rates in order to remove airborne bacteria from the rooms. However, extremely large ventilation rates are needed to effectively remove the infectious particles from the room, and the effectiveness of the removal becomes progressively less as ventilation rate is increased. Research has shown that although ventilation systems lessen the chance of infection by dispersing bacteria, the increase of ventilation rate does not, as a whole, guarantee good control to the spreading airborne infection. Also, negative pressure can be used as a preventative measure, and this is created by exhaust fans which remove the contaminated air and create a pressure differential that reduces the flow of bacteria to other areas. In locations where airflow control is not feasible or cost-effective, high efficiency particulate air (HEPA) filters are used in air ducts to disinfect the air. However, proper installation, maintenance and monitoring of the HEPA filters are essential.

Another means of minimizing the risk from airborne bacteria within an isolation room is to apply ultraviolet germicidal irradiation (UVGI) to the area. UVGI is defined as optical radiation in the short-wave UV-C spectrum capable of killing certain airborne bacteria. Ultraviolet lighting has been shown to reduce, but not eliminate, the threat of infection by killing bacteria in confined spaces. UVGI potentially holds promise of greatly lowering the concentration of airborne bacteria and thus controlling the spread of airborne infection among occupants in an enclosed space.

Ultraviolet radiation has a wavelength range that is shorter than visible light but longer than x-rays; its range extends from 100 to 400 nanometers (nm) and is divided into three zones; UV-A, long wave (320 nm – 400 nm); UV-B, medium wave (280 nm – 320 nm); and UV-C, short-wave (100 nm-280 nm). Ultraviolet radiation is a component of sunlight. UV-A is responsible for the tanning effect, whereas UV-C contains the most effective disinfection wavelengths. Close-range exposure to the bare lamps that emit UVGI can cause superficial eye and skin irritation. However, the use of specially designed lamp fixtures for upper-room UVGI applications ensures that occupants will only be exposed indirectly to low UV-C intensities. UVGI is generated by lamps made specifically for this purpose and should not be mistaken with lamps that produce higher UV wavelengths that are used for tanning, medical (e.g., psoriasis therapy), industrial (e.g., curing plastics), or commercial (i.e., black light) purposes. Nor should the short-wave ultraviolet wavelengths produced by germicidal lamps be confused with the long wave UV in sunlight that can cause skin cancers and cataracts of the eye due to overexposure.

The use of UVGI is not a new phenomenon. Simple UV fixtures were developed and used during the 1940s and 1950s for air disinfection. During the 1980s, when the cases of TB rose dramatically, these machines were unsuitable for modern medical facilities due to lower ceiling heights. In particular, patients were subject to unacceptable levels of radiance to their eyes and skin. However, more recent lamp designs, which utilize louvers to reduce exposure in the lower regions of the room, are capable of maintaining UV intensities to around 0.1 $\mu W/\ cm^2$.

Currently, the most widely used applications of UVGI are in the form of passive upper-room fixtures containing UVGI lamps that irradiate a horizontal layer of airspace above the occupied zone. These units are quiet, easy to maintain and very cost-effective. These lamps are designed to kill bacteria that enter this upper irradiated zone, and are highly reliant on vertical room air currents. The survival probability of bacteria after being exposed to UVGI depends on the UV irradiance as well as the exposure time in a general form (Federal Register (1993)):

$$\% \, Survival = 100 \times e^{-kIt} \tag{1.1}$$

Where I = UV irradiance, $\mu W/cm^2$
t = time of UV exposure
k = microbe susceptibility factor, $cm^2/\mu W.s$

Increasing room air mixing enhances upper-room UVGI effectiveness by bringing more bacteria into the UV zone. However, rapid vertical air circulation also implies insufficient exposure time. It must be understood and considered that the ability to remove or kill bacteria in isolation rooms is greatly influenced by the flow pattern of ventilation air. Some of the parameters which affect these matters are listed below:

- Ventilation flow rate
- Locations of air supplies/exhausts
- Supply air temperature
- Location of the UV fixture(s)
- The power of the UV output
- Room configuration
- Susceptibility of the particular species of bacteria

In order to achieve a better performance of UVGI, as well as higher removal effectiveness within the ventilation system, the airflow patterns need to be fully understood and well organized. Therefore, it is necessary to conduct a systematic study in order to address minimizing the risk from airborne organisms in hospital isolation rooms while all the important parameters are being analyzed.

Previous research has been almost entirely based on empirical methods (Chang et al. (1985), Macher et al. (1992), Mortimer et al. (1995)), which are time-consuming and tend to be limited by the cost of modifying physical installations of the ventilation systems. The absence of UV treatment systems has also imposed limitations on previous research. Therefore, design guidance for isolation rooms in the past has often relied on gross simplifications without fully understanding the effect of the complex interactions of room airflow and UV treatment systems. It should be noted that, although this study looks specifically at isolation rooms, same principles can be applied to other regions in which infection from TB is a possibility, such as waiting rooms, or other areas within a healthcare facility.

Computational Fluid Dynamics, or CFD, (sometimes known as airflow modeling) expresses the principles of conservation of mass, momentum and thermal energy within a fluid. The basis of CFD is formed into a solution that may be expressed in terms of partial differential equations and has been proven to be very powerful and efficient in research projects involving parametric studies on room airflow and contaminant dispersion (Jiang et al.(1997), Jiang et. al (1995), Haghighat et al. (1994)). The solution is carried out iteratively based on a set of coupled algebraic equations that relate the value of many small volumes (grid cells) within a system. For this reason, CFD is employed as the main approach in the present study. The output of CFD simulations can be presented in many ways, adding to the value of the method. For example, useful details such as field distributions can be displayed, as well as overviews on the effects of parameters involved. Further, an algorithm was developed which allowed the particles to be tracked through the room studied, and which allowed the UV dosage to be calculated for the particle. From this data, such information such as the number of particles vented by the ventilation system, the number of particles killed by UV, and the number of viable particles in the room at any time could be established.

SECTION V

RESULTS

SECTION V: TABLE OF CONTENTS

5. RESULTS

5.1 Description of Results Presentation

There are basically two mechanisms of removing particles from the room in this study: ventilation, and UVGI killing. The status of the particles can be defined accordingly as:

- Vented out (considered killed)
- Airborne, killed by UV (killed)
- Airborne, not killed (viable)

At the starting time of the particle tracking, i.e., t = 0 seconds, 2700 viable particles are released into the room. As time progresses, some of the particles are killed by UVGI, and some of them are removed from the room by ventilation. As a result, the number of viable particles remaining in the room reduces with time. The status of these particles after a certain period of tracking time indicates the effectiveness of ventilation and UVGI, and are examined for a tracking period of 300 s (5 minutes). An increase in tracking time may result in lower survival probability for bacteria.

In this study, the 2700 particles are analyzed under 40 different room airflow conditions. With each airflow condition, three UV energy fields are considered. Therefore, 120 (3 x 40) particle-tracking runs are performed to investigate the removal effectiveness of the ventilation system and UVGI. In the particle tracking routine, the status of the particles at each time step, ranging between 1e-4 s to 1e-6 s, is recorded. To present the results, however, the time interval of 1e-6 s is too small. Therefore, an interval of 60 seconds is taken in the graphic representations of the results. In other words, the numbers of vented, viable and killed particles are presented graphically at the end of every 60-second time interval. The surviving fraction is also presented at the same time interval. As the 2700 particles progress through the flow and UV fields, the dose received by each particle is different. Therefore, graphs are presented to show the distribution of dose bands for every time interval (60 s) for each of the 120 particle tracking analyses.

The fate of the particles are considered for 9 different parametric changes as follows:

- Ventilation flow rate (winter condition)
- Ventilation flow rate (summer condition, peak temperature)
- Ventilation flow rate (summer condition, peak cooling load)
- Exhaust location (winter, without baseboard heating)
- Exhaust location (summer condition, peak temperature)

- With/without Baseboard heating (low exhausts)
- Exhaust location (winter, with baseboard heating)
- Pressurization of the room (winter condition)
- Pressurization of the room (summer condition)

Note that the numbers of particles in different dose bands do not include the particles that are already vented out.

5.2 Notes on Calculation of Derived Parameters

The notes that follow are numbered according to their occurrence in the results section.

Note 1:

The vented out particles are not used in the calculation of the average UV dosage of the remaining, viable particle population.

Note 2:

Viable particles with the group counting method are defined as the particles that are:

- Not vented out
- Not killed by UV

Note that only viable particles contribute to the average UV dose in calculating the percentage of surviving particles.

Note 3:

For group counting, the number of particles classed as killed is calculated as follows.

Number of killed particles = Number of viable particles * (1 – (survival percentage for population/100))

The survival percentage is calculated based on the average dose of all viable particles. At the beginning of the next time interval, the particles which are tagged as being killed are no longer included in the calculation of the survival percentage. The tagged particles are those which have the highest individual UV total dose.

In order to clarify how the particles are classified, Table 5.1 lists the particle numbers in different status at the end of every minute for Case10 (Summer 10 ACH). The summation of airborne (viable plus part of particles killed by UV) and vented out particles at the end of any minute is 2700.

Table 5.1 Budget Table for 2700 Particles (Case 10 with group counting)

	End of Min 1	**End of Min 2**	**End of Min 3**	**End of Min 4**	**End of Min 5**
Vented out	62	335	508	675	851
Dead vented-out	0	40	74	142	235
Viable	2638(1)	1984 (4)	1508	1119	875
% Surviving	84 (2)	83	80.8	85.6	85.5
Killed	421 (3)	758	1048	1209	1344

(1) As the UV killing calculation is at the end of the first time interval, all particles remaining in the room after one minute are assumed to be viable.

(2) The average UV total dose for the viable particle population is used in the calculation of the survival percentage.

(3) Number of killed particles = Number of viable particles * (1 – (survival percentage for population/100))

Number of killed particles = 2638*(1-(84/100)) = 421

(4) The summation of viable, killed in the previous time interval and vented out particles does not match 2,700, the number of total particles from the second interval onwards. This is because the number of vented out particles includes the killed particles as well. Note that the dead-vented particles must be subtracted from the total particle count to avoid “double counting”. For example at the end of Minute 3, the balance shows:

1508 (viable) + 758 (killed in the previous minute) +508 (vented) – 74 (dead-vented) = 2,700

Note 4:

For individual counting, the survival probability of each individual particle and a random number (which determines which *specific* particles will be killed), will determine whether the particle is killed or not. The budget of the 2700 particles at the end of each time interval with the individual counting method for Case10 is presented in Table 5.2. Again, note that the dead-vented particles must be subtracted from the total particle count to avoid "double counting". For example at the end of Minute 3, the balance shows:

1259 (viable) + 994 (killed) +508 (vented) – 61 (dead-vented) = 2,700

Table 5.2 Budget Table for 2700 Particles (Case 10 with individual counting)

	End of Min 1	**End of Min 2**	**End of Min 3**	**End of Min 4**	**End of Min 5**
Vented out	62	335	508	675	851
Dead vented-out	0	27	61	133	228
Killed	323	684	994	1205	1367
Viable	2315	1708	1259	953	710

Note 5:

The survival fraction is calculated with Equation 4.2. The surviving fraction presented in the figures is only associated with group counting method.

Note 6:

The number of particles vented out will be presented only with UV1 since they are not affected by the UVGI location and output power change.

5.3 Results

As stated in SECTION IV, two locations of the UV lamp fixture and three UVGI output power levels are considered in combinations, which result in three different UV intensity distributions used in particle tracking analysis. They are:

- UV1: Output power of 10W, located on the partition wall, 7.5' from the floor.
- UV2: Output power of 20W, located on the wall near the bed, 7.5' from the floor.
- UV3: Output power of 40W, located on the wall near the bed, 7.5' from the floor.

For UV1, the following 6 sets of plots are presented:

- The number of particles removed by ventilation varying with time for every 60s
- The number of viable particles varying with time for every 60s – with group counting

- The number of viable particles varying with time for every 60s – with individual counting
- The number of particles killed by UV dosage varying with time for every 60s - with group counting method
- The number of particles killed by UV dosage varying with time for every 60s - with individual counting method
- The survival fraction of particles varying with time for every 60s

All plots presented for UV1 are repeated for UV2 and UV3, except for the number of vented out particle plots because, as noted above, the number of particles removed by ventilation system is independent of UV distribution.

Each set of results includes 9 plots for each group indicated in Section 5.1, which represent the 9 different parameters considered.

There are also two comparisons shown in Section 5.3:

- Comparison of Performances of UVGI and ventilation for different ACH
- Comparison of Performances of UVGI and ventilation for different UV output. In this case, additional cases are considered with the UV lamp located above the bed for the sake of completeness.

The dose bands for the 120 particle-tracking analyses are presented in Section 5.3 as well.

Also included are the results for the number of vented, killed and viable particles at the end of the 300s period for both the group and individual killing mechanisms, and the three different UV locations and powers. This information provides a means of checking the effectiveness of the UV and ventilation system against the various parameters considered.

Finally in Section 5.3, an analysis of the current costs associated with the installation of UVGI against increased ventilation rates is included.

5.3.1 Number of Vented Out Particles Varying with Time (UV1)

UV1: UVGI output power 10W, located on the partition wall, 7.5’ from the floor.

Figures 5.1 to 5.3 show that the number of vented out particles increases when the ventilation flow rate increases for both winter and summer cases. The range is more pronounced for winter cases than for summer cases. In summer, peak load conditions, the increase of ventilation flow rate does not show as much benefit as in summer peak temperature conditions.

The high exhaust allows more particles to be vented out than low exhausts as seen in Figures 5.4 and 5.5, except for the winter case with the highest flow rate considered (16 ACH) This is probably due to the fact that the high turbulence in the upper region prevents the particles released from the low positions from following the streamlines and being vented out.

In Figure 5.6, it is seen that baseboard heating in winter cases slightly reduces the effectiveness of ventilation in terms of particle removal. Figure 5.7 compares the high and low exhausts with baseboard heating used. High exhausts again result in slightly a higher number of vented out particles.

The vented out particle number does not seem to be sensitive to increased pressurization of the room, as shown in Figures 5.8 and 5.9.

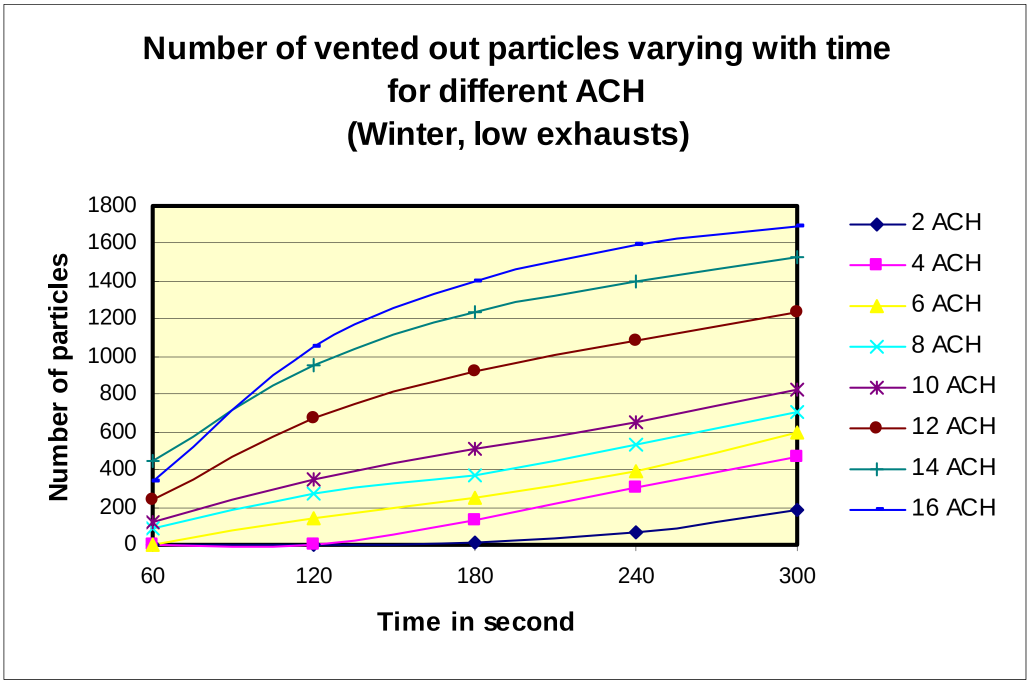


Figure 5.1. Number of vented out particles with ACH change (Winter)

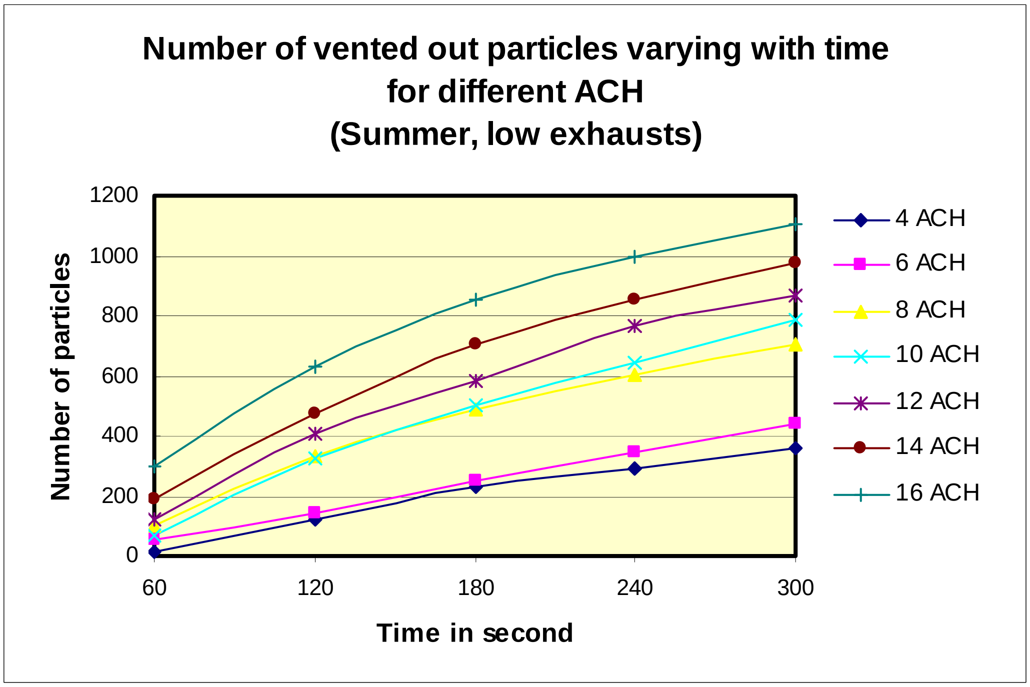


Figure 5.2. Number of vented out particles with ACH change (Summer)

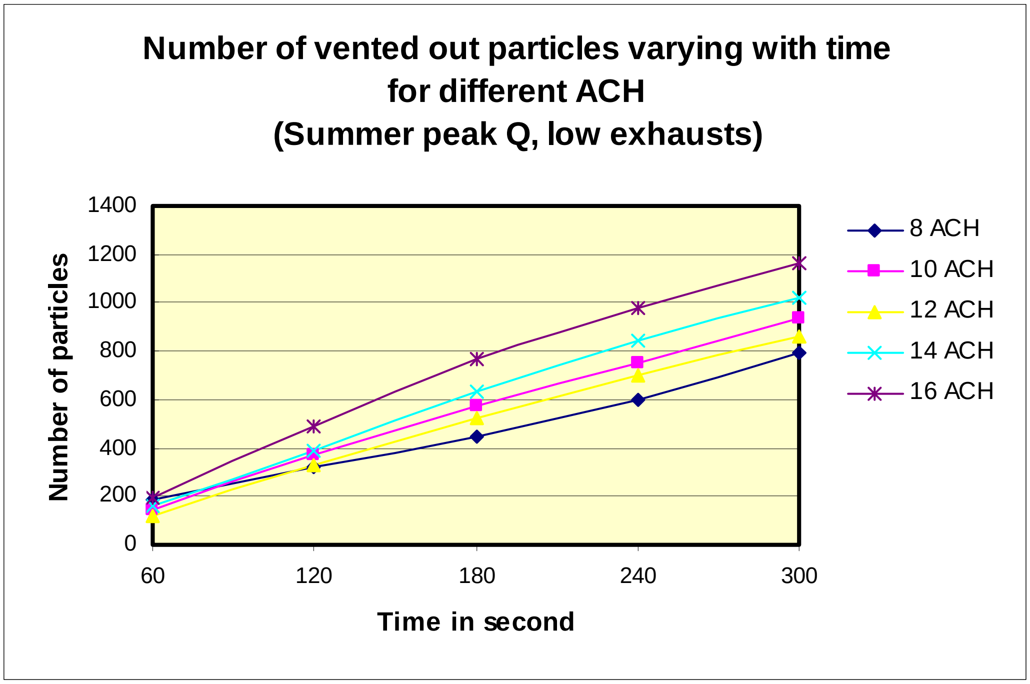


Figure 5.3. *Number of vented out particles with ACH change (Summer peak Q)*

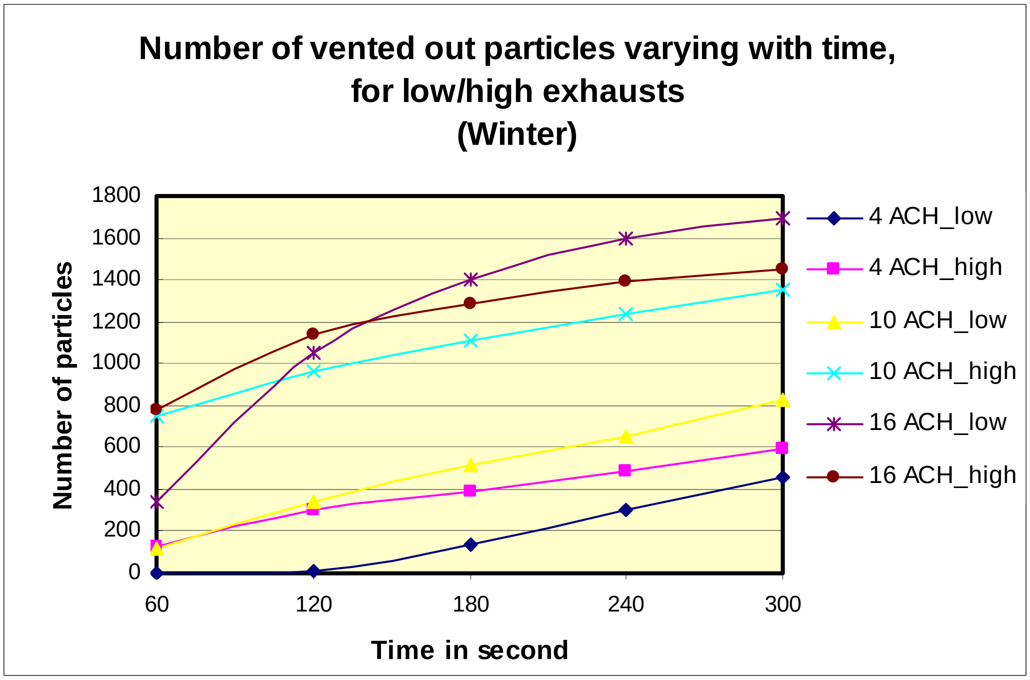


Figure 5.4. *Number of vented out particles with exhaust location change (Winter)*

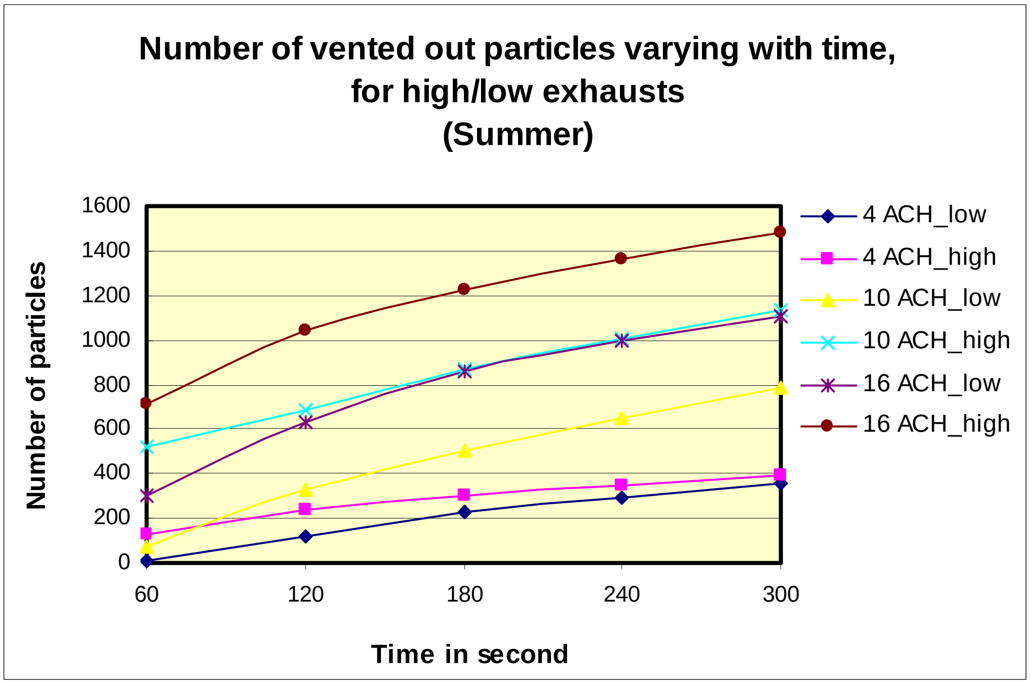


Figure 5.5. *Number of vented out particles with exhaust location change (Summer)*

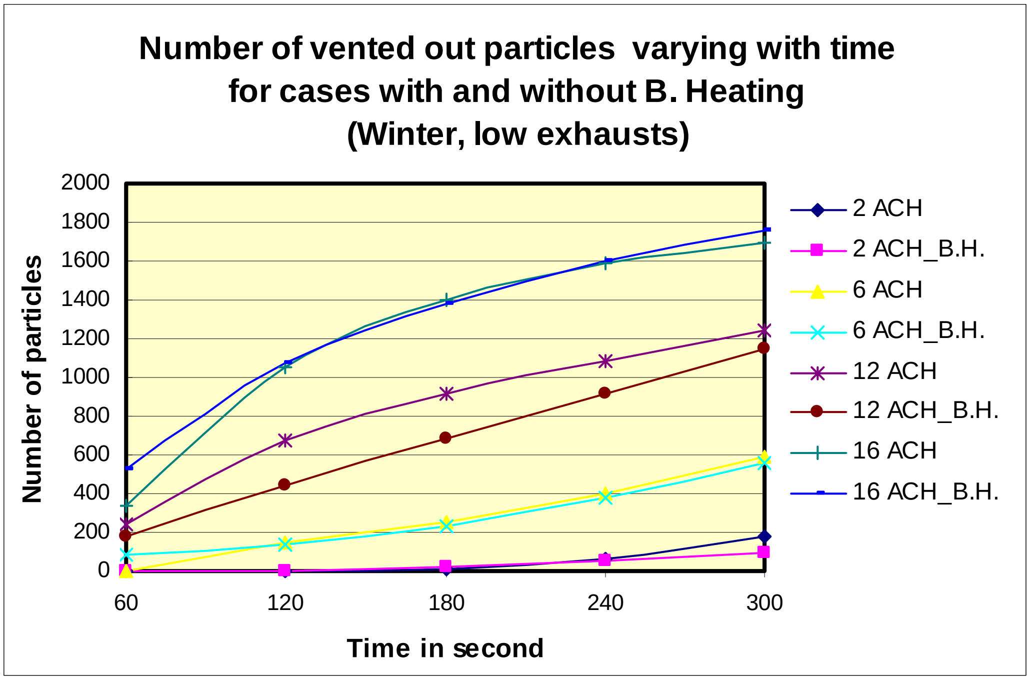


Figure 5.6. *Number of vented out particles for cases with/without Baseboard Heating*

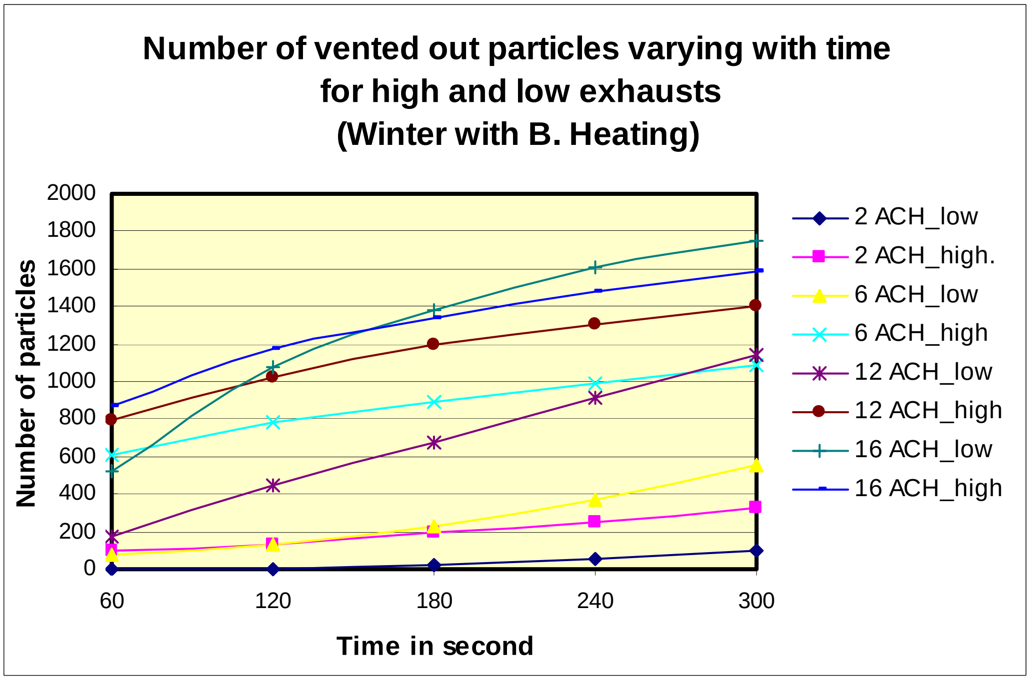


Figure 5.7. *Number of vented out particles for exhaust location change when baseboard heating is applied*

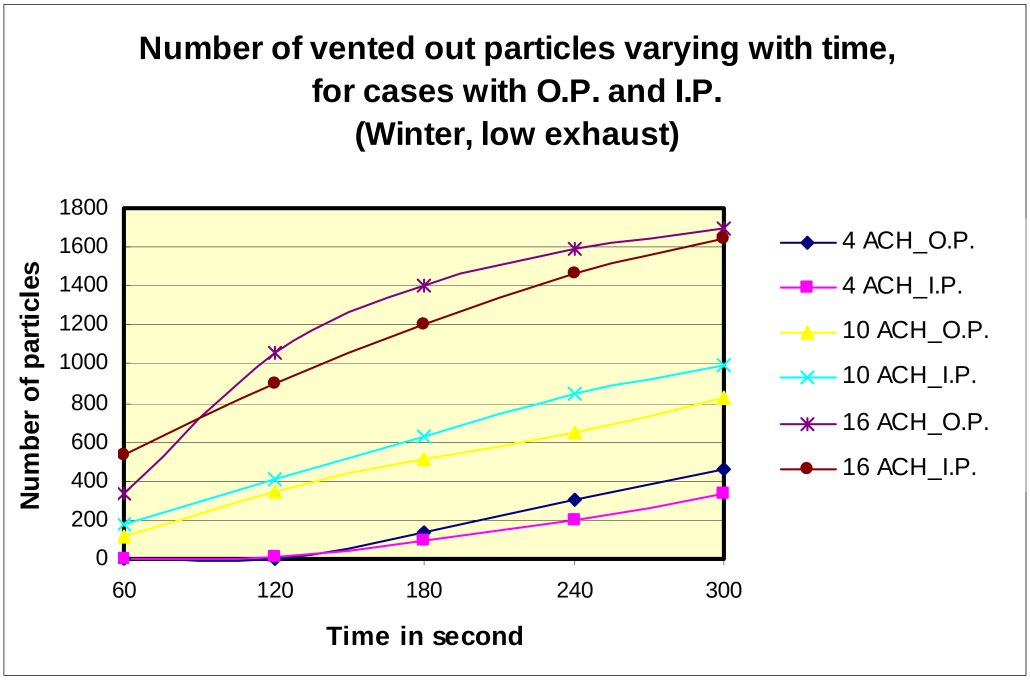


Figure 5.8. *Number of vented out particles for cases with original/ increased pressurization (Winter)*

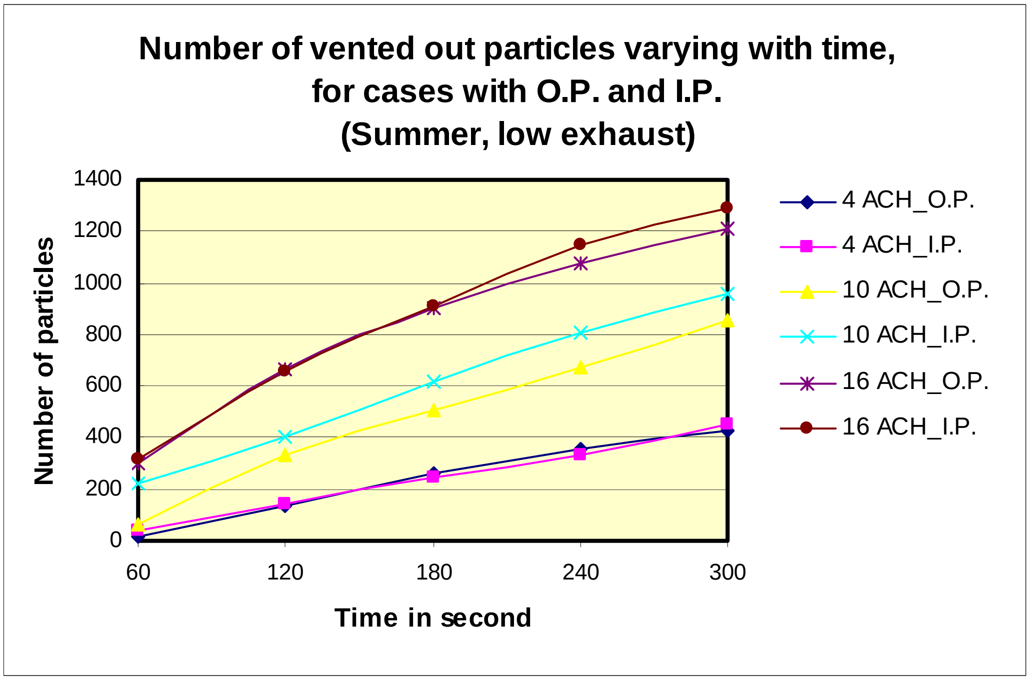


Figure 5.9. *Number of vented out particles for cases with original/ increased pressurization (Summer)*

5.3.2 Number of Viable Particles –Group Counting -Varying with Time (UV1)

UV1: UVGI output power 10W, located on the partition wall, 7.5’ from the floor.

Figure 5.10 shows that an increase in the ventilation rate for winter conditions results in lower number of viable particles. The same tendency cannot be found in summer cases, especially for the cases with peak load, in which number of viable particle is insensitive to the increase of flow rate as seen in Figure 5.12.

Figure 5.13 indicates that for winter cases, the viable particle number becomes lower if moving the exhausts to high position. The same conclusion can be applied to summer cases, but the phenomenon is less pronounced as shown in Figure 5.14.

Figure 5.15 indicates that baseboard heating in winter conditions results in lower number of viable particles when the exhausts are low. However increasing the flow rate higher than 10 ACH results in diminishing returns. Figure 5.16 compares the high and low exhausts with baseboard heating used, which shows that exhaust location does not make much different concerning the number of viable particle.

Increased pressurization of the room, as shown in Figures 5.17 and 5.18, slightly reduces the number of viable particles for both winter and summer cases.

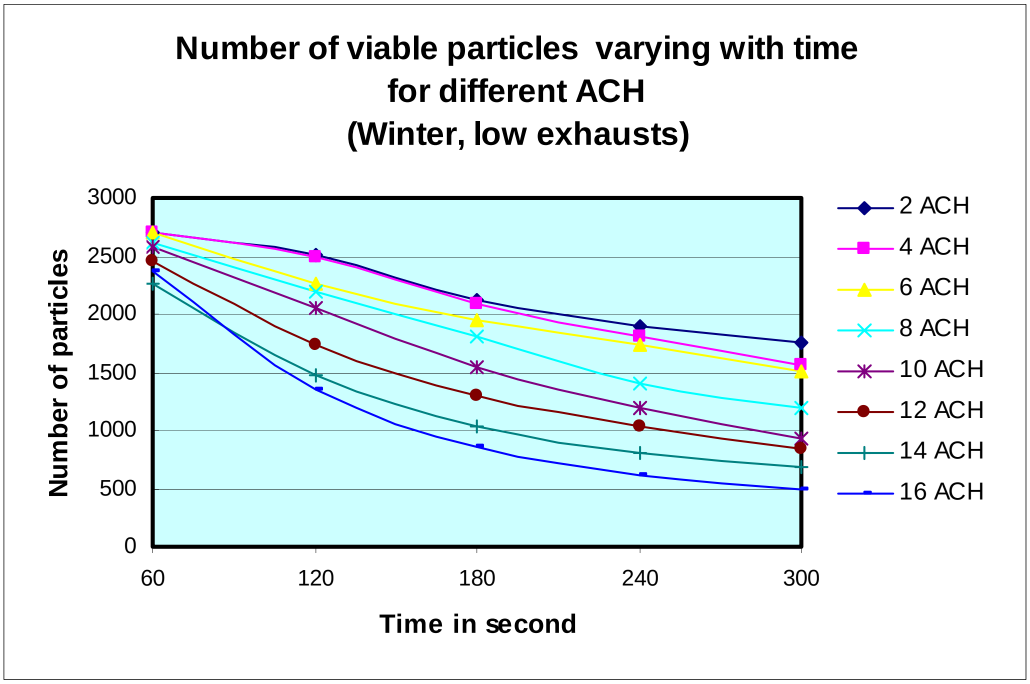


Figure 5.10. *Number of viable particles with ACH change (Winter)*

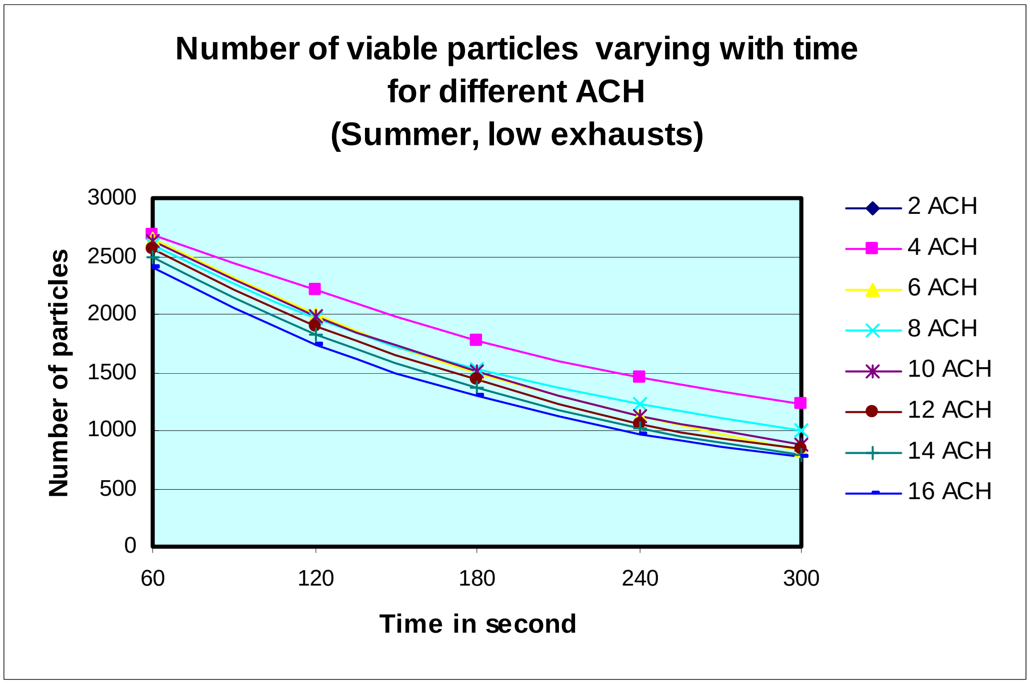


Figure 5.11. *Number of viable particles with ACH change (Summer).*

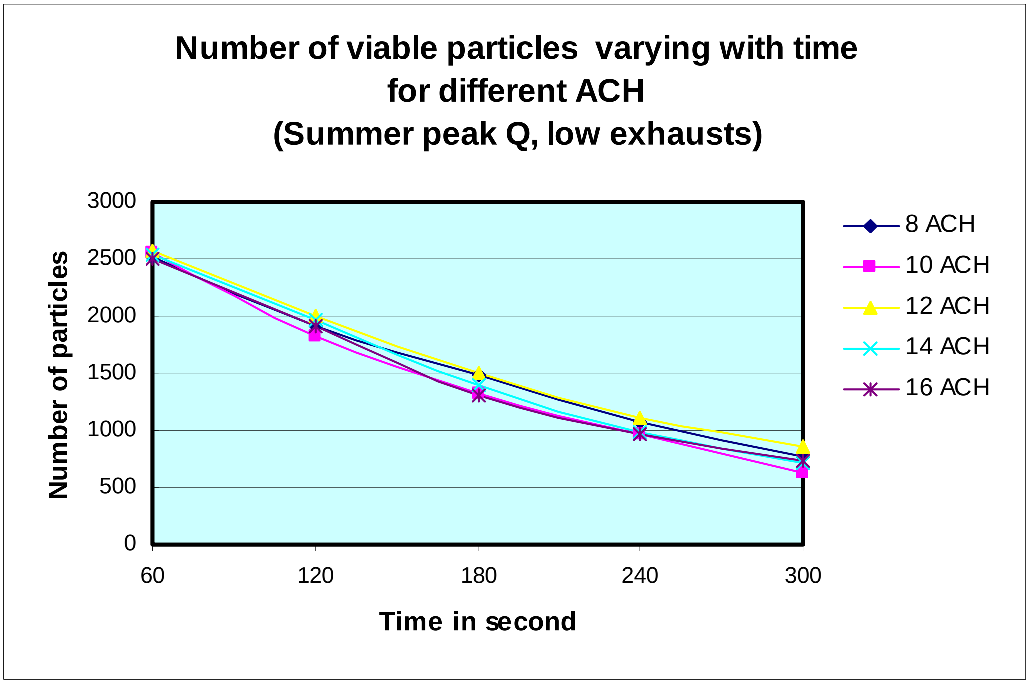


Figure 5.12. *Number of viable particles with ACH change (Summer peak Q).*

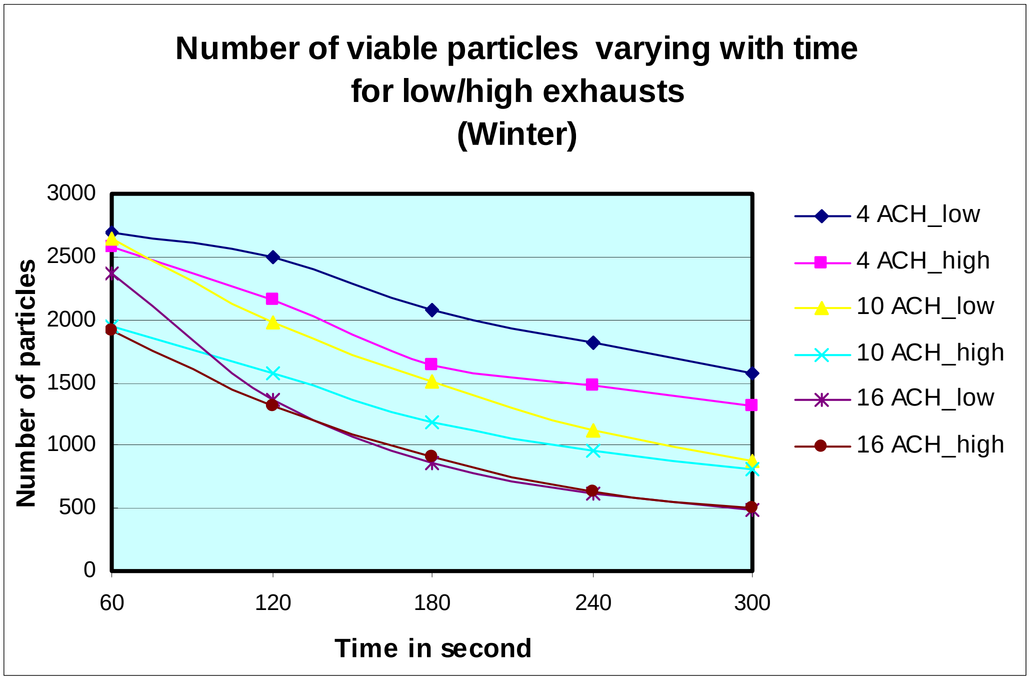


Figure 5.13. *Number of viable particles with exhaust location change (Winter).*

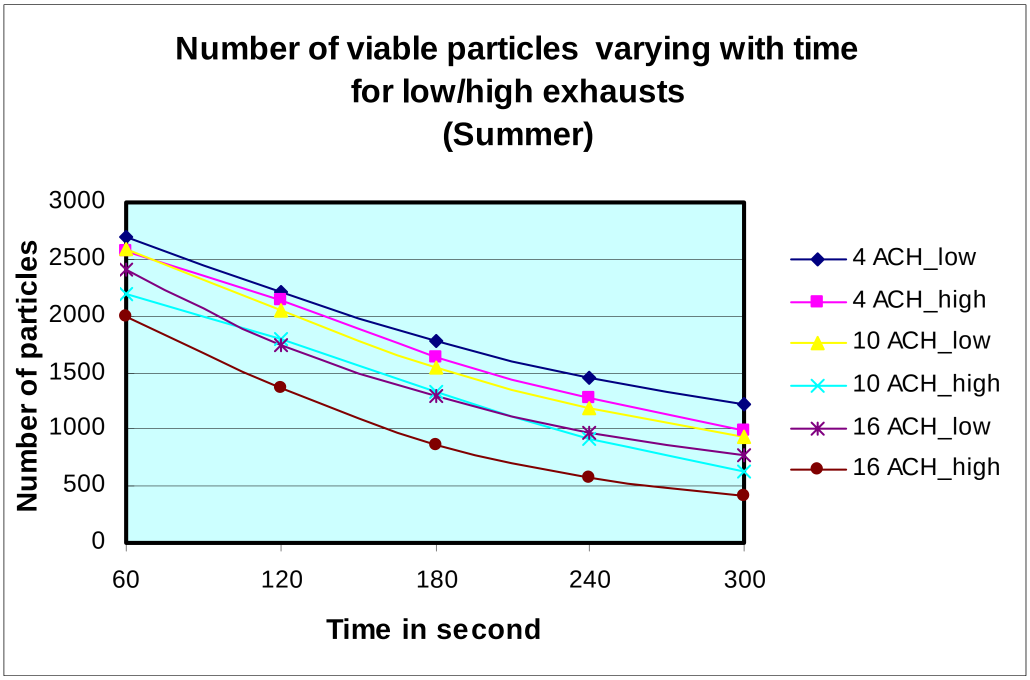


Figure 5.14. *Number of viable particles with exhaust location change (Summer).*

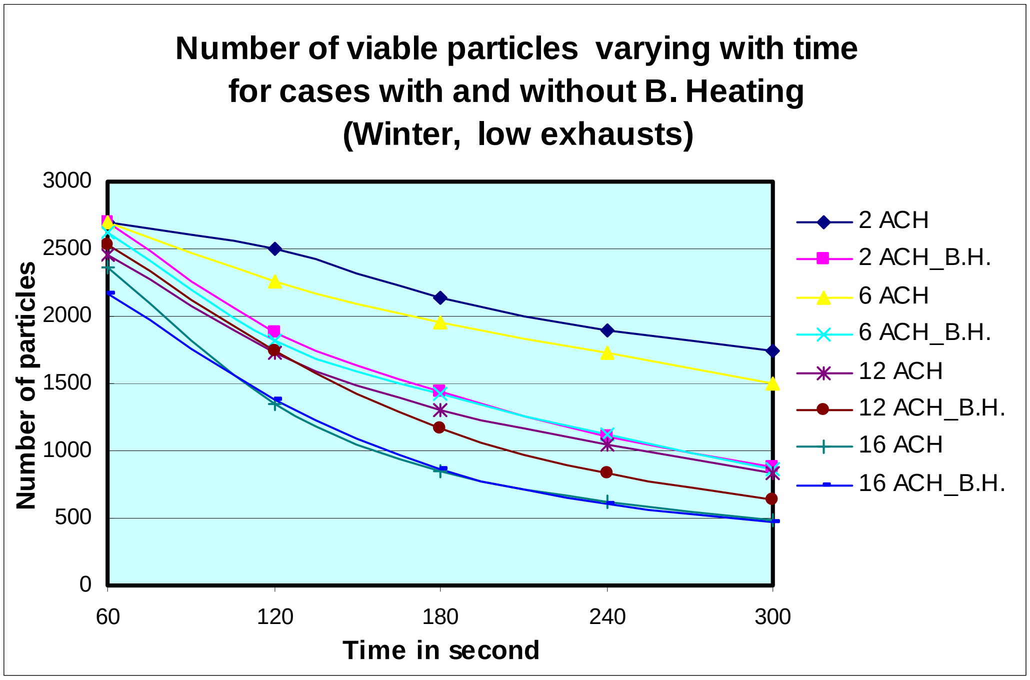


Figure 5.15. *Number of viable particles for cases with/ without Baseboard Heating.*

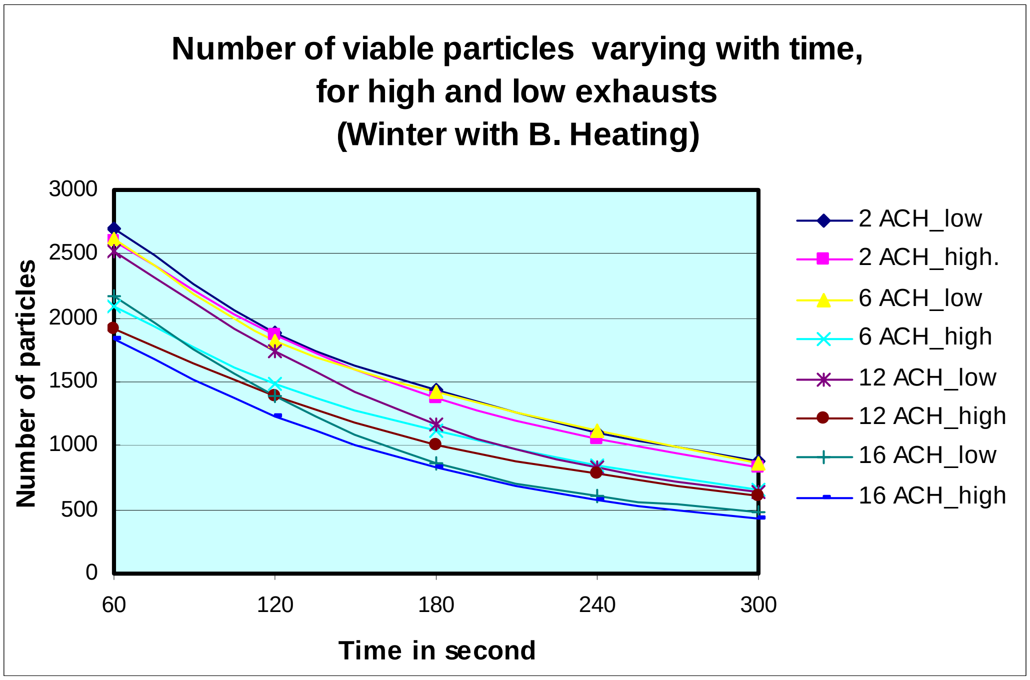


Figure 5.16. *Number of viable particles for exhaust location change when baseboard heating is applied*

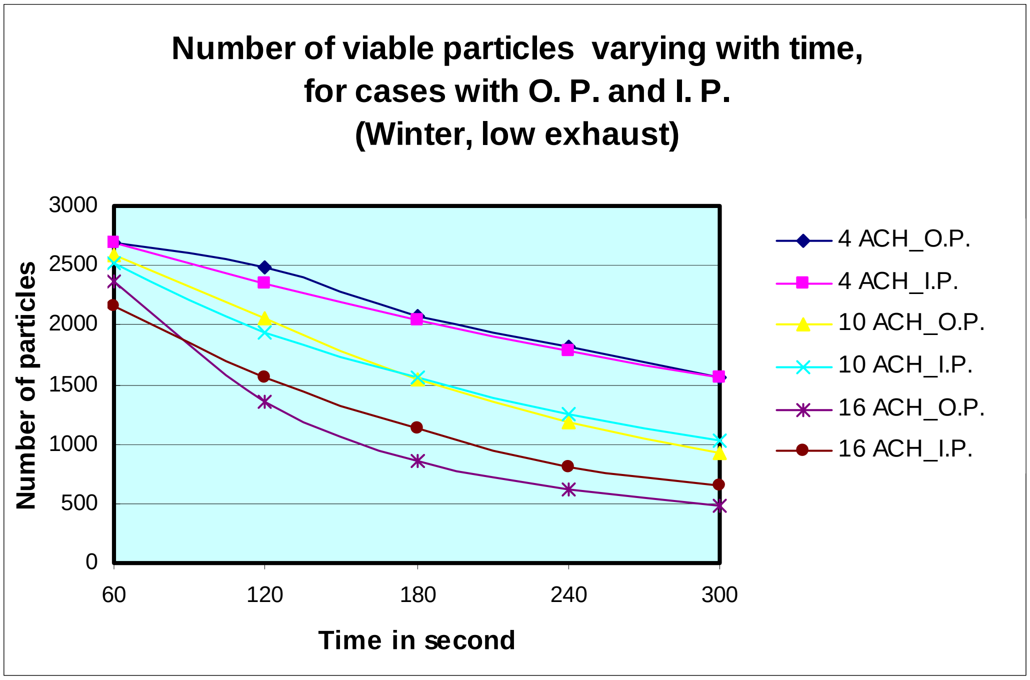


Figure 5.17. *Number of viable particles for cases with original/ increased pressurization (Winter)*

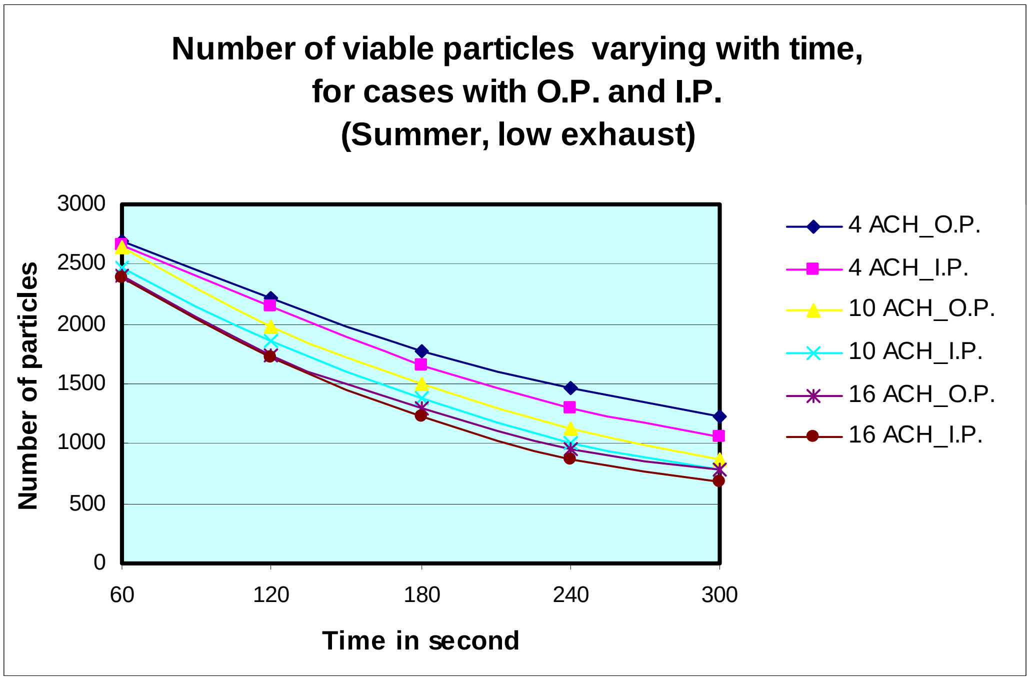


Figure 5.18. *Number of viable particles for cases with original/ increased pressurization (Summer)*

5.3.3 Number of Viable Particles – Individual Counting -Varying with Time (UV1)

UV1: UVGI output power 10W, located on the partition wall, 7.5’ from the floor.

For UV1, the observations in the number of viable particles with group counting are generally valid with individual counting. Figure 5.19 shows that an increase in the ventilation rate for winter conditions results in lower number of viable particles. In summer conditions, the viable number with individual counting is insensitive to the ventilation flow rate, as seen in Figures 5.20 and 5.21.

From Figures 5.22 and 5.23, it is observed that, the viable particle number becomes lower if moving the exhausts to high position.

Figure 5.24 indicates that baseboard heating in winter conditions results in lower number of viable particles when the exhausts are low. However increasing the flow rate higher than 10 ACH results in diminishing returns. Figure 5.25 compares the high and low exhausts with baseboard heating used, which shows that exhaust location does not make remarkable difference concerning the number of viable particle with individual counting.

Increased pressurization of the room, as shown in Figures 5.26 and 5.27, slightly reduces the number of viable particles for both winter and summer cases.

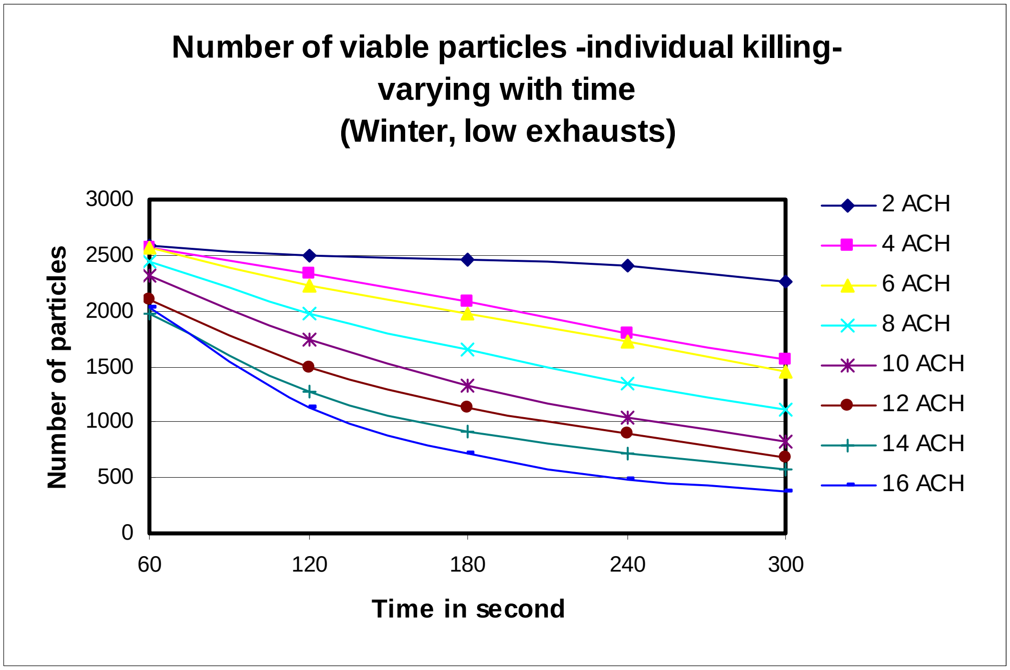


Figure 5.19. *Number of viable particles with ACH change (Winter)*

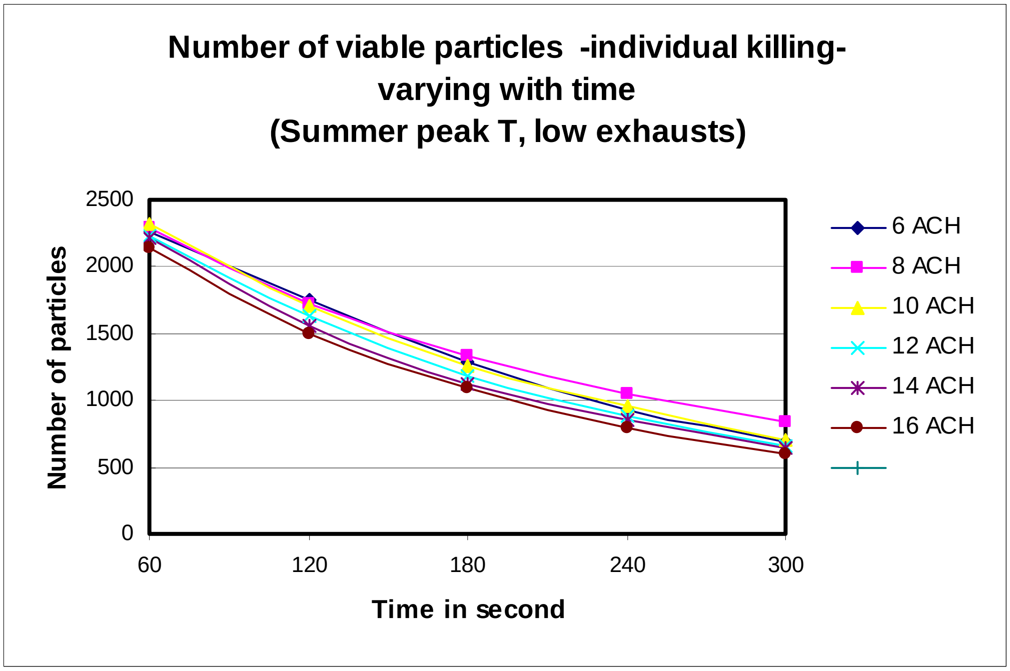


Figure 5.20. *Number of viable particles with ACH change (Summer).*

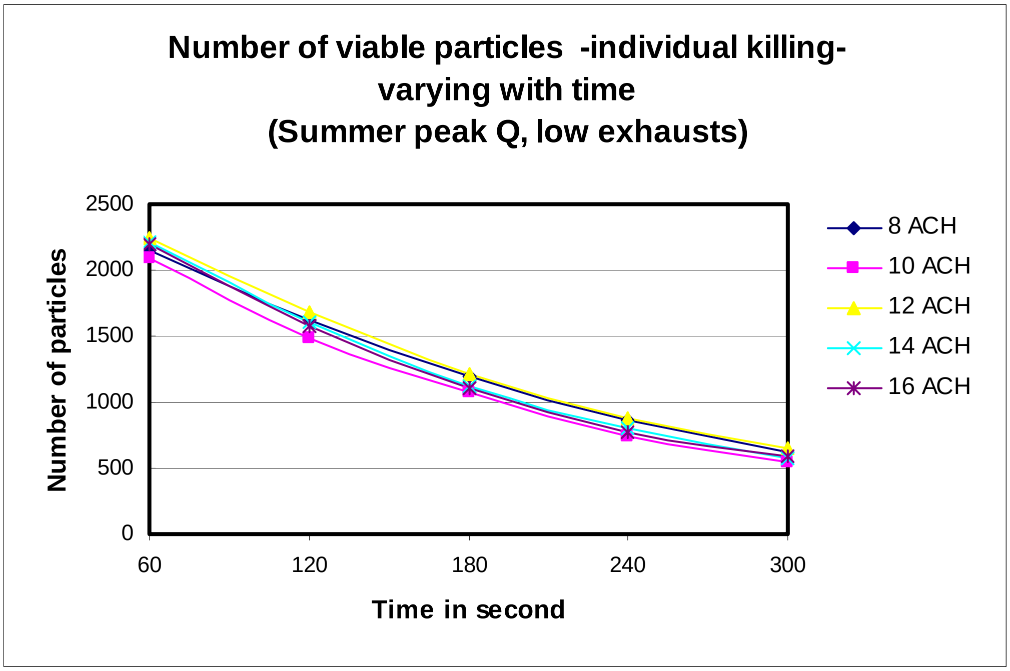


Figure 5.21. *Number of viable particles with ACH change (Summer peak Q).*

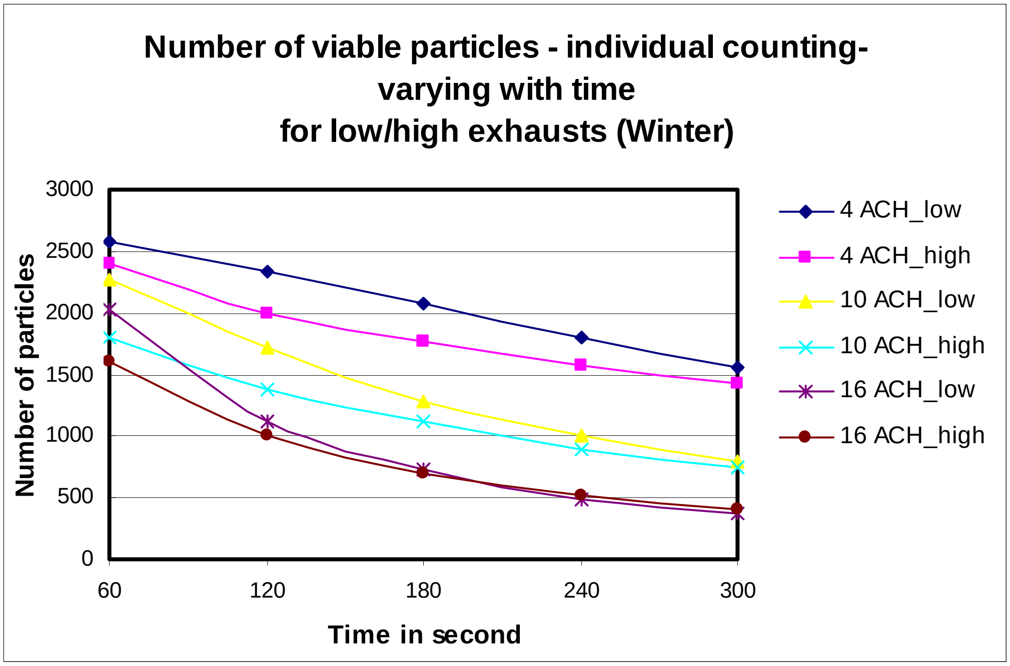


Figure 5.22. *Number of viable particles with exhaust location change (Winter).*

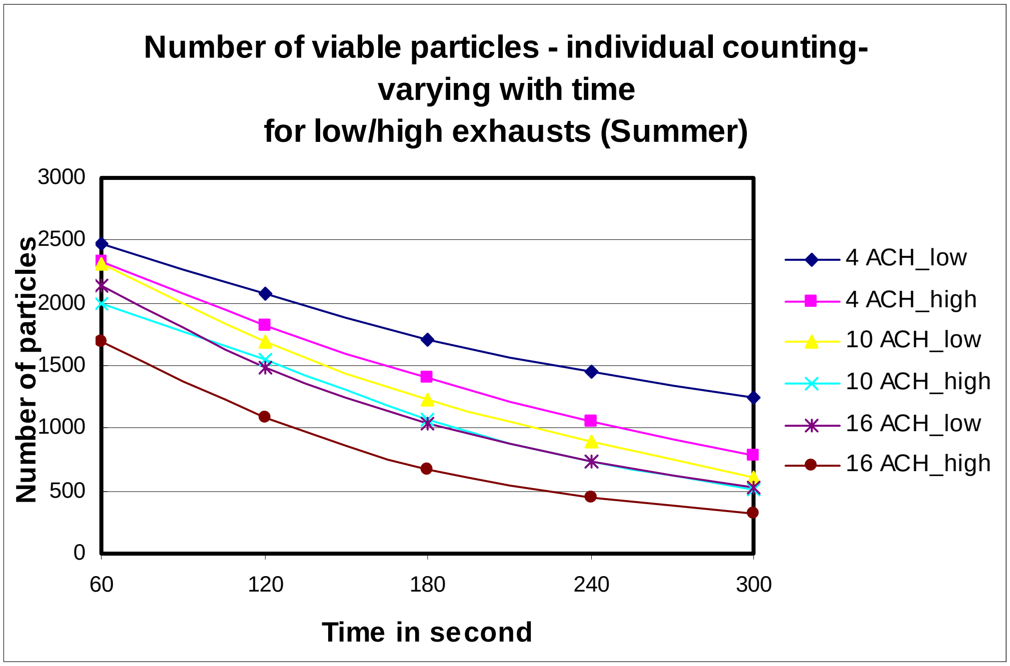


Figure 5.23. *Number of viable particles with exhaust location change (Summer).*

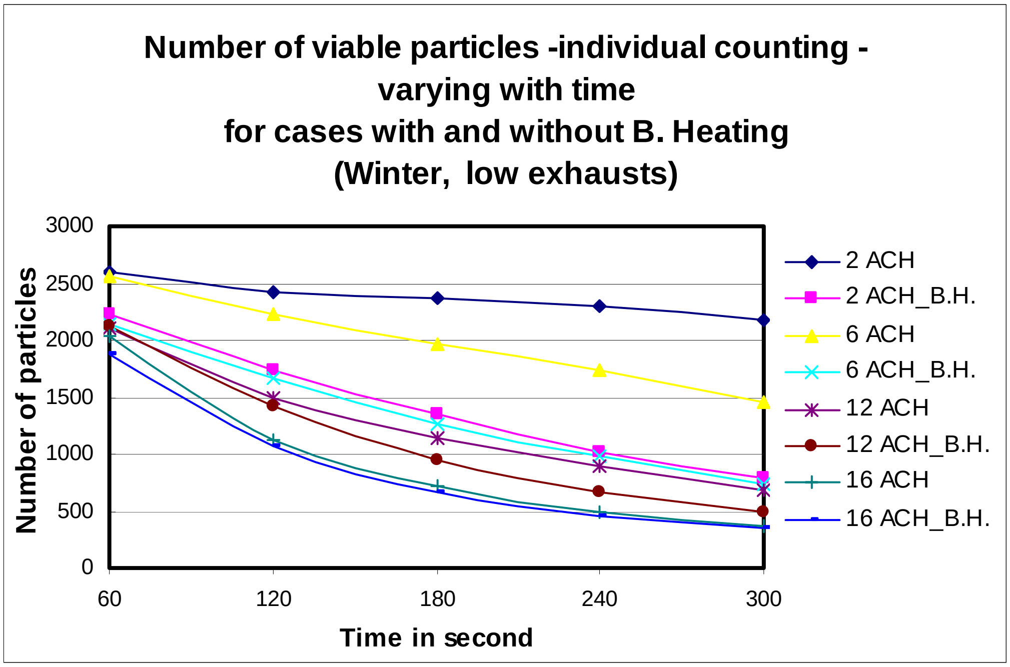


Figure 5.24. *Number of viable particles for cases with/ without Baseboard Heating.*

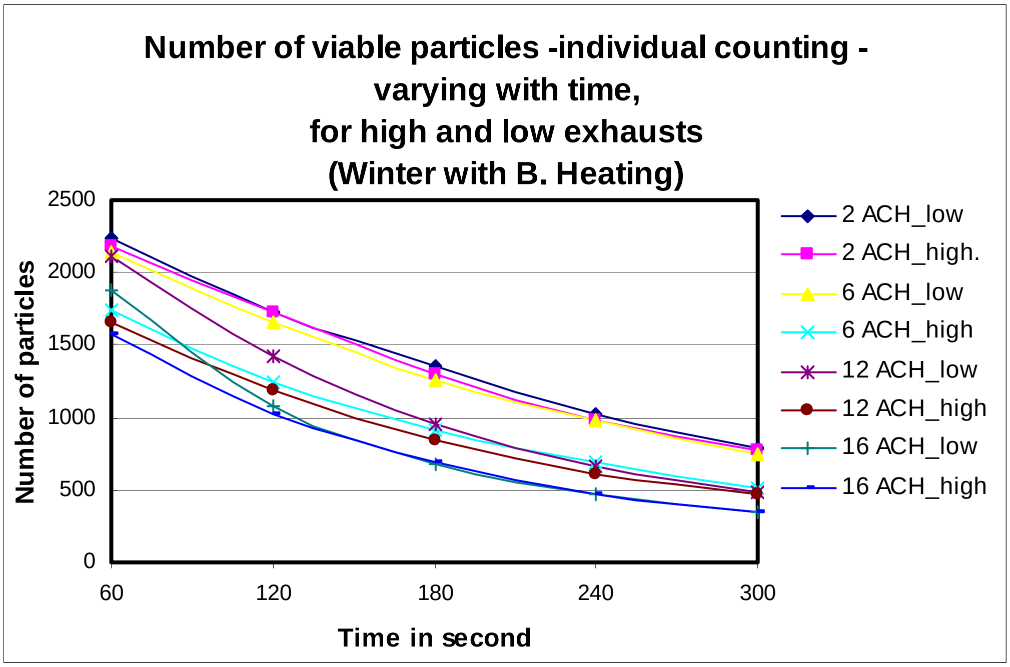


Figure 5.25. *Number of viable particles for exhaust location change when baseboard heating is applied*

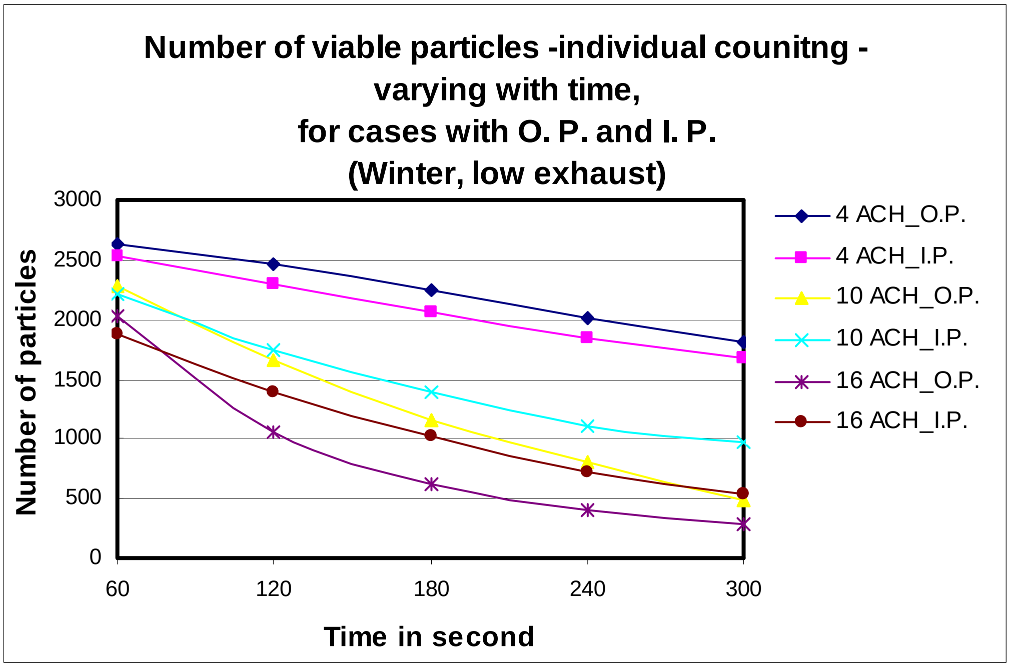


Figure 5.26. *Number of viable particles for cases with original/ increased pressurization (Winter)*

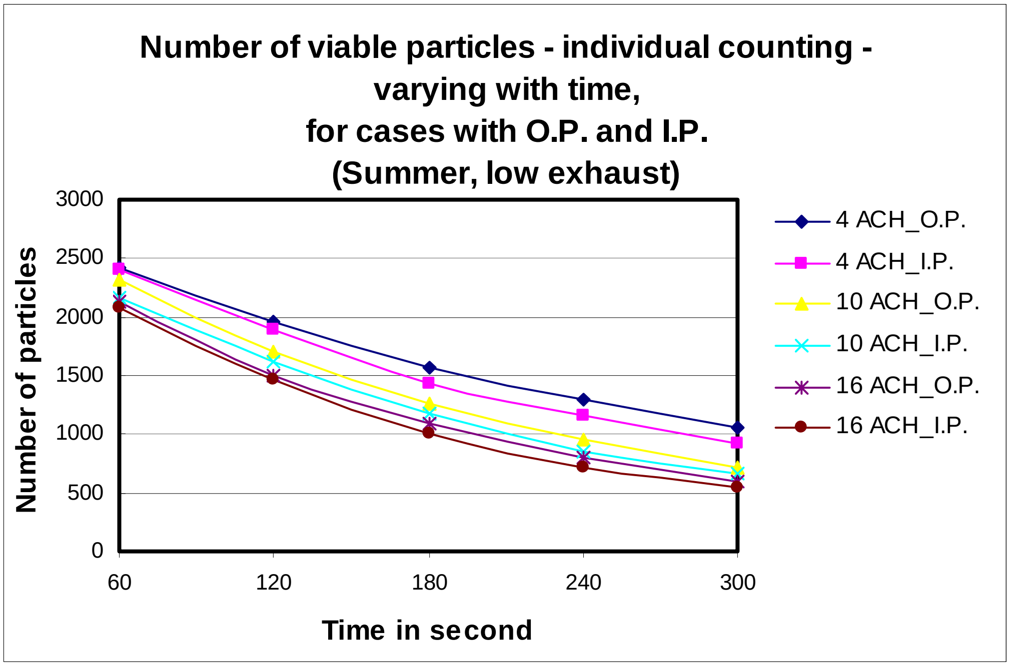


Figure 5.27. *Number of viable particles for cases with original/ increased pressurization (Summer)*

5.3.4 Number of Killed Particles - Group Counting - Varying with Time (UV1)

UV1: UVGI output power 10W, located on the partition wall, 7.5’ from the floor.

Figure 5.28 shows that, for winter cases with no baseboard heating, 10 ACH gives the highest number of killed particles. Further increase of the ventilation does not result in a higher number of particles killing. This tendency is observed in the summer cases, but the cut-off point occurs at a different ventilation rate. For summer conditions, the best ventilation flow rate falls between 6-10 ACH (See Figures 5.29 and 5.30).

Figure 5.31 indicates that for winter cases, the killed particle number generally becomes higher if moving the exhausts to high position, except for the case with 16 ACH. The same can be applied to summer cases as shown in Figure 5.32.

Figure 5.33 indicates that baseboard heating significantly increases the number of killed particles when the exhausts are low. However, it is not worth further increasing the flow rate from 10 ACH. Figure 5.34 compares the high and low exhausts with baseboard heating used, which shows that low exhausts result in higher number of killed particles by UVGI.

Increased pressurization of the room in winter condition reduces the killed number only for middle range of flow rate (10 ACH), indicated in Figure 5.35. For summer cases, no significant effect is observed, as shown in Figure 5.36.

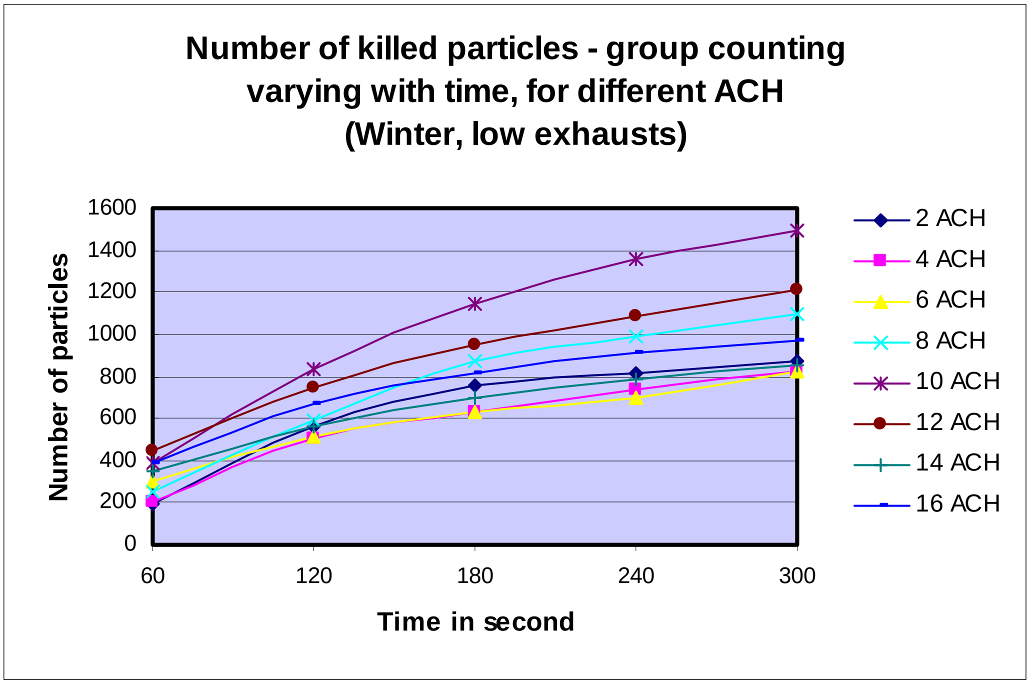


Figure 5.28. *Number of killed particles with ACH change (Winter)*

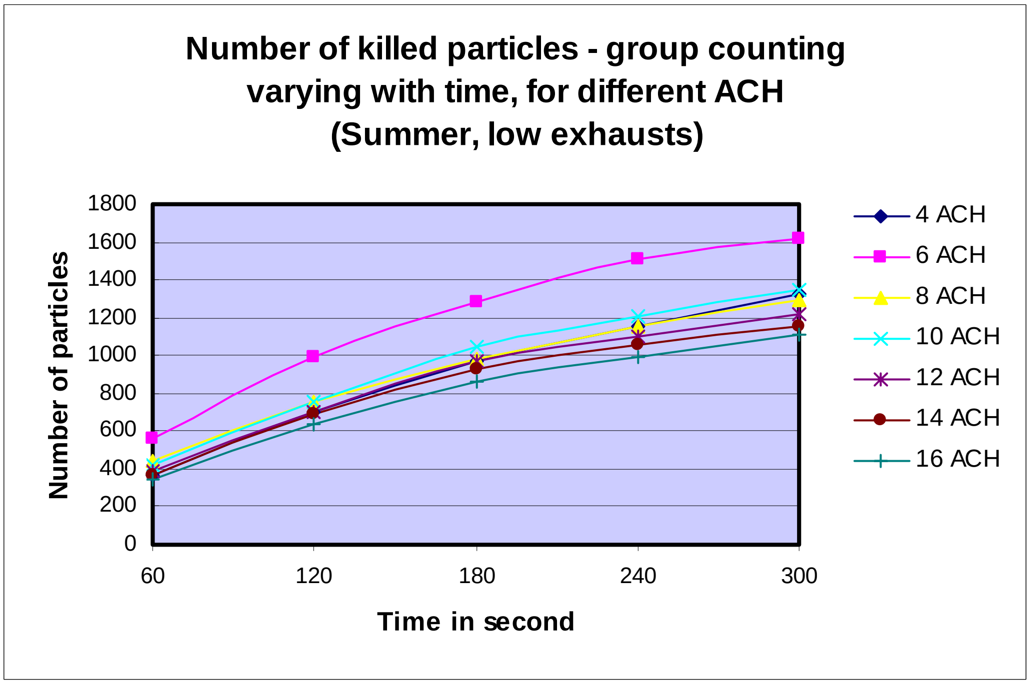


Figure 5.29. *Number of killed particles with ACH change (Summer)*

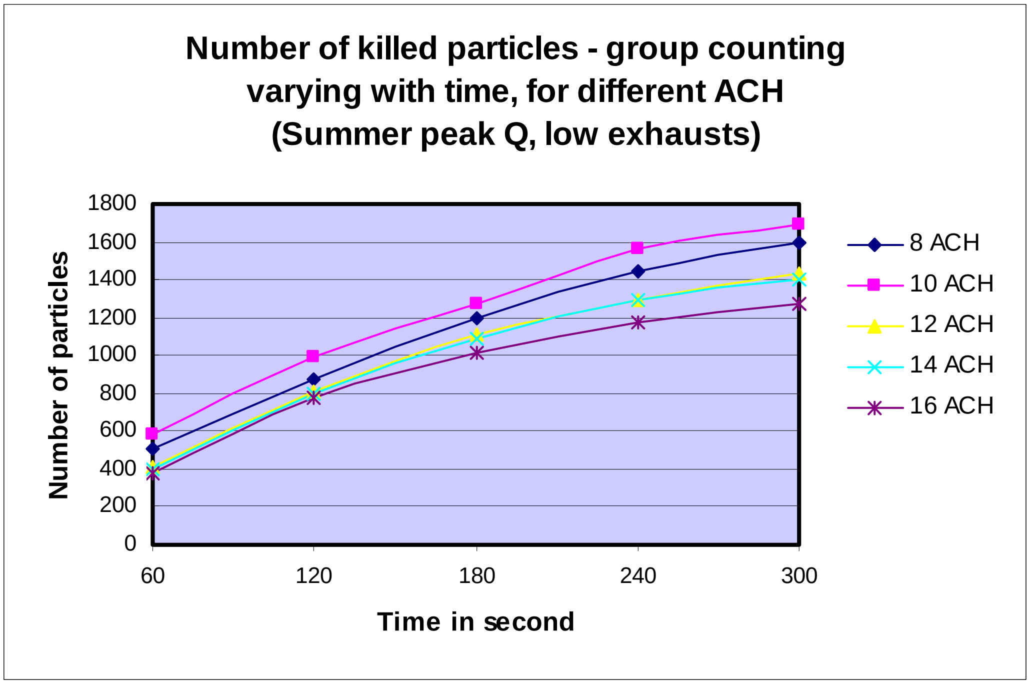


Figure 5.30. *Number of killed particles with ACH change (Summer peak Q)*

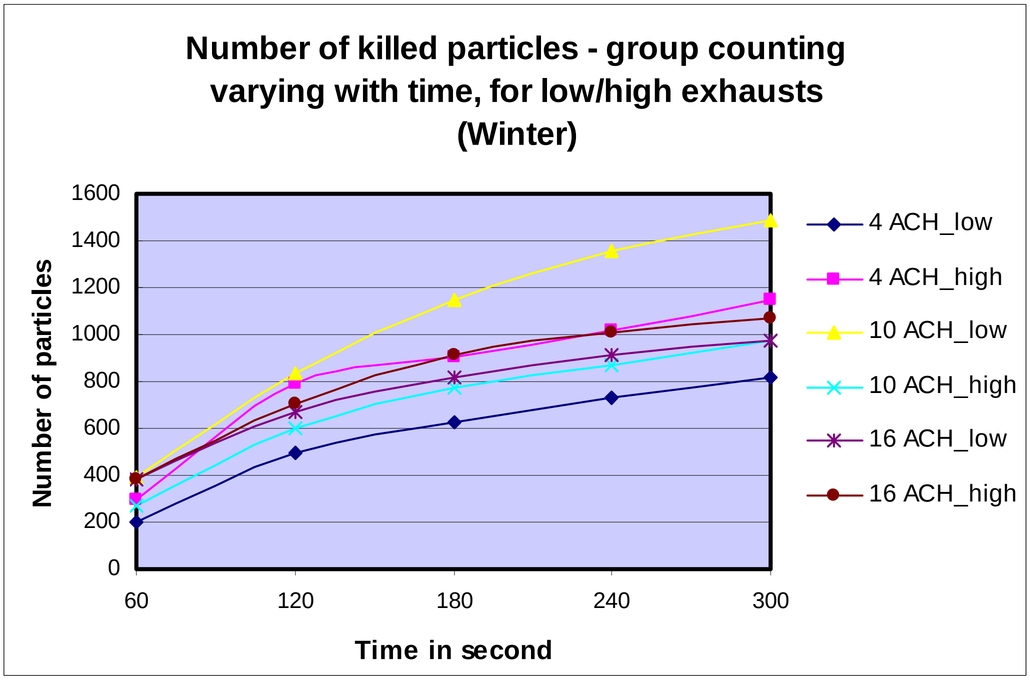


Figure 5.31. *Number of killed particles with exhaust location change (Winter)*

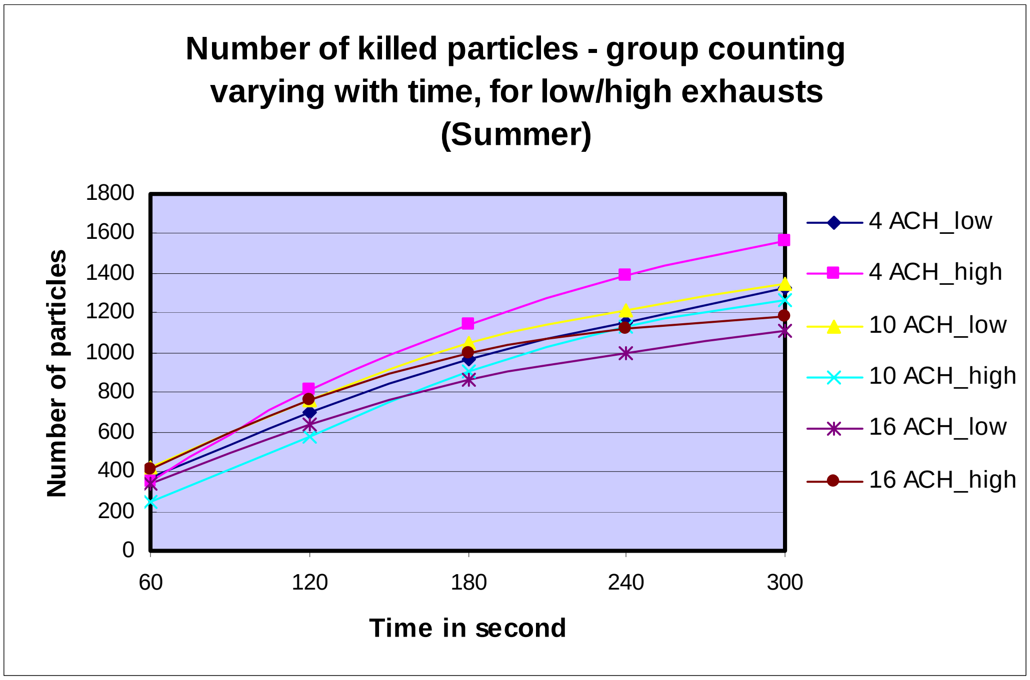


Figure 5.32. *Number of killed particles with exhaust location change (Summer)*

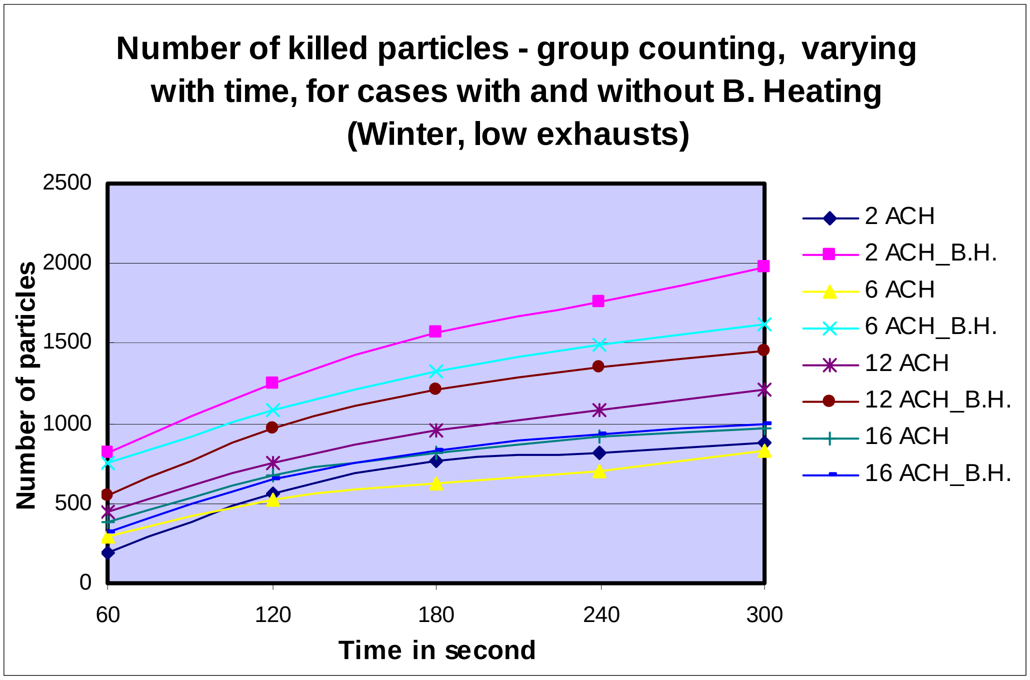


Figure 5.33. *Number of killed particles for cases with/without Baseboard Heating*

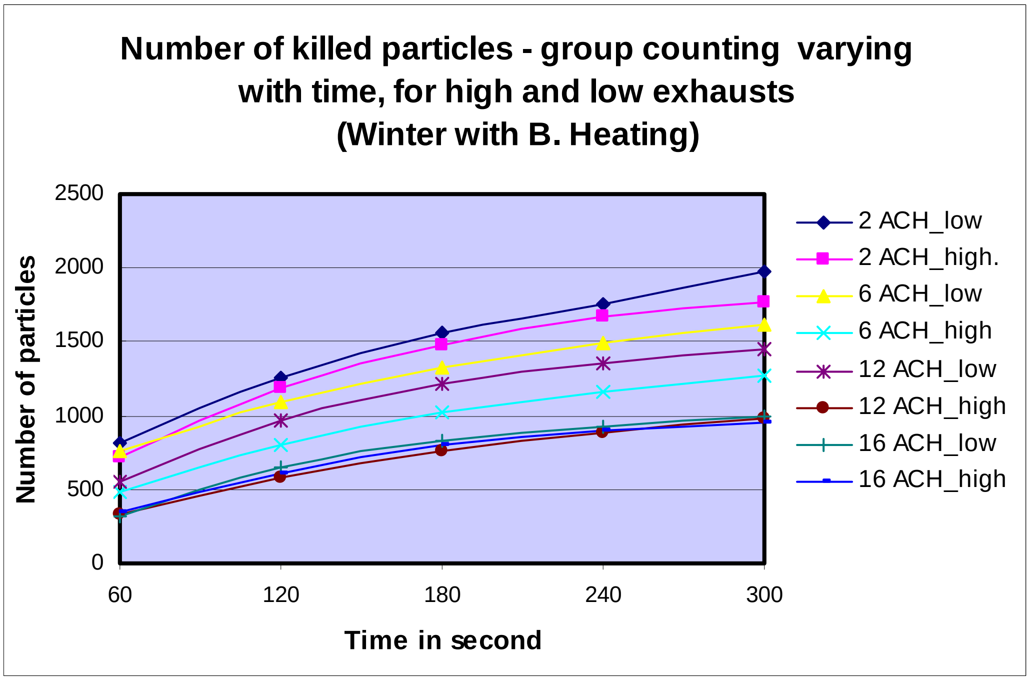


Figure 5.34. *Number of killed particles for exhaust location change when baseboard heating is applied*

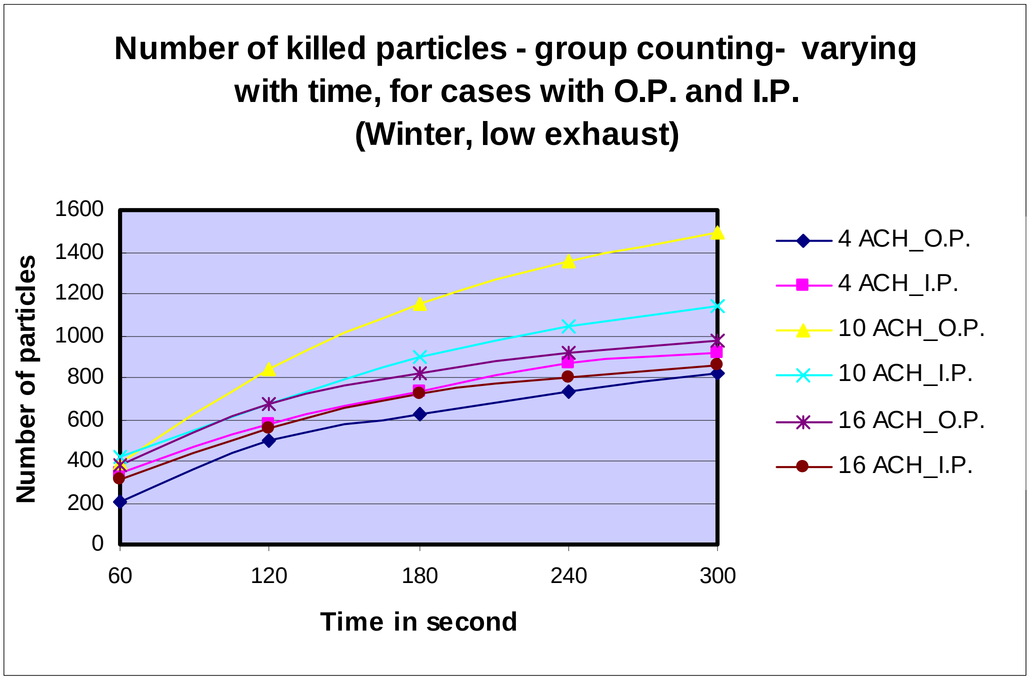


Figure 5.35. *Number of killed particles for cases with original/ increased pressurization (Winter)*

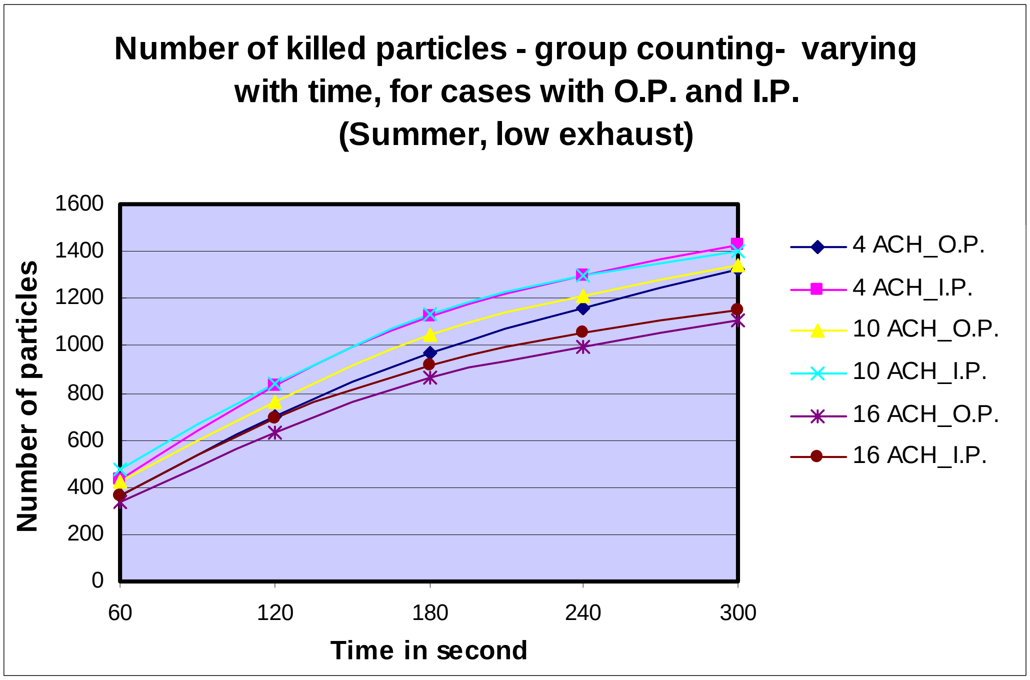


Figure 5.36. *Number of killed particles for cases with original/ increased pressurization (Summer)*

5.3.5 Number of Killed Particles - Individual Counting - Varying with Time (UV1)

UV1: UVGI output power 10W, located on the partition wall, 7.5’ from the floor.

The conclusions drawn for the number of killed particles in group counting (see the last section) can be generally applied here, except for the comparison of high/low exhaust location without baseboard heating.

Figure 5.37 shows that, for winter conditions, 10 ACH gives the highest number of killed particles. A further increase of the ventilation does not result in higher number of particles killing. This tendency is observed in summer cases, but at a different flow rate. For summer condition, the best ventilation flow rate falls between 6-10 ACH (See Figures 5. 38 and 5.39).

Figure 5.40 shows that, for winter conditions, high exhaust location gives higher number of killed particle when the flow rate is below 16 ACH. Figure 5.41 shows that summer cases show no obvious tendency as to which exhaust location gives better UV killing

Figure 5.42 indicates that baseboard heating significantly increases the number of killed particles when the exhausts are low. However, it is not worth further increasing the flow rate from 10 ACH. Figure 5.43 compares the high and low exhausts with baseboard heating used, which shows that low exhausts result in higher number of killed particles by UVGI.

Increased pressurization of the room in winter condition reduces the killed number only for middle range of flow rate (10 ACH), indicated in Figure 5.44. For summer cases, no significant effect is observed, as shown in Figure 5.45.

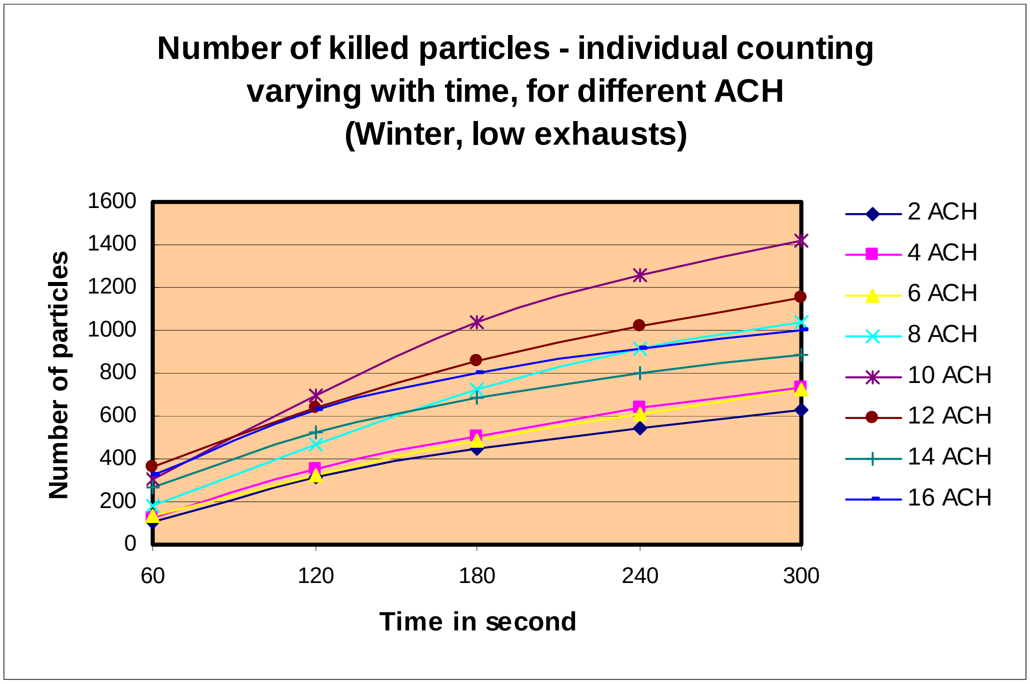


Figure 5.37. *Number of killed particles - individual counting - with ACH change (Winter)*

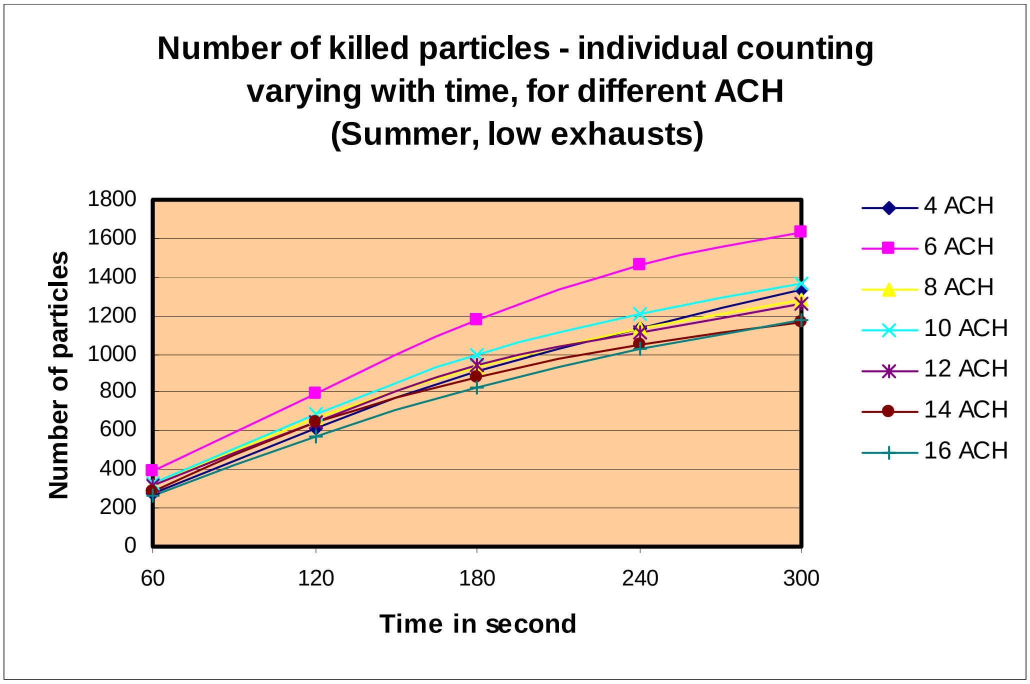


Figure 5.38. *Number of killed particles - individual counting - with ACH change (Summer)*

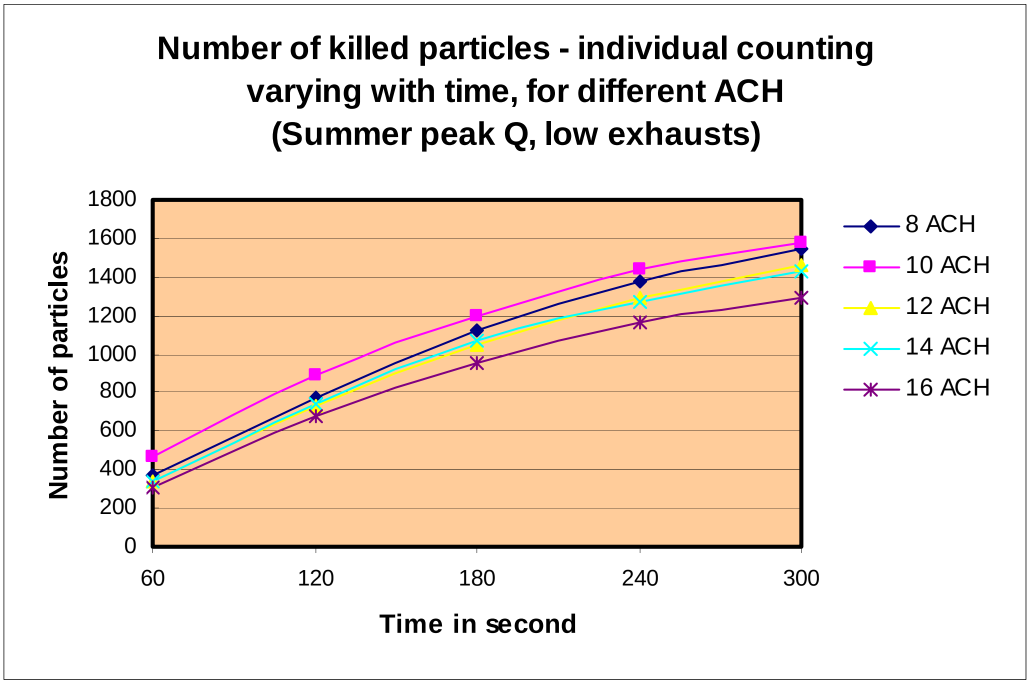


Figure 5.39. *Number of killed particles - individual counting - with ACH change (Summer peak Q)*

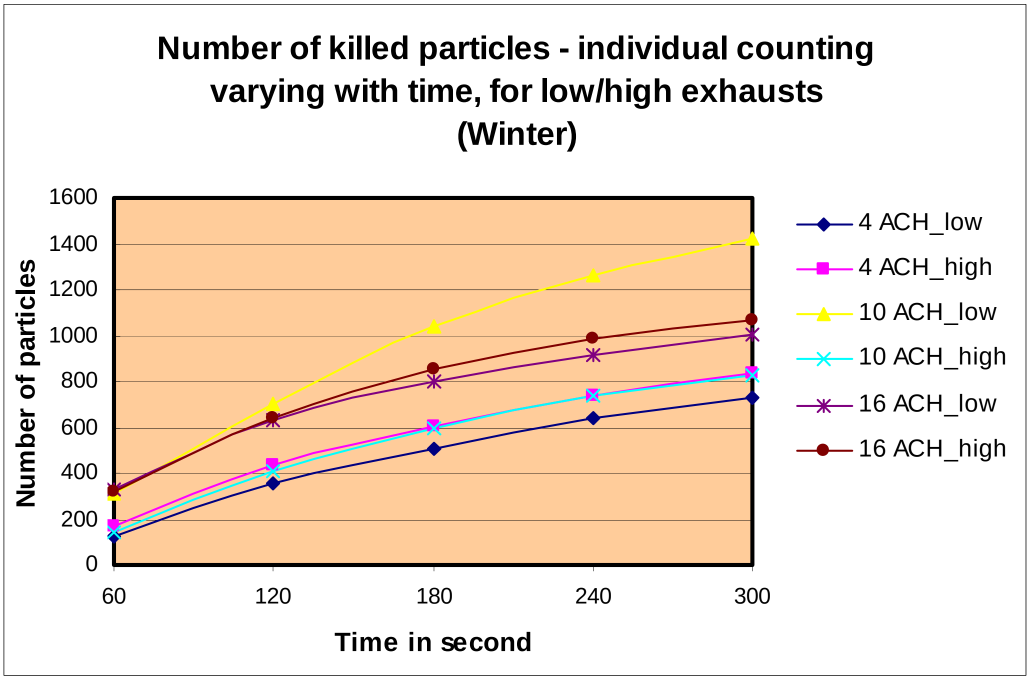


Figure 5.40. *Number of killed particles - individual counting - with exhaust location change (Winter)*

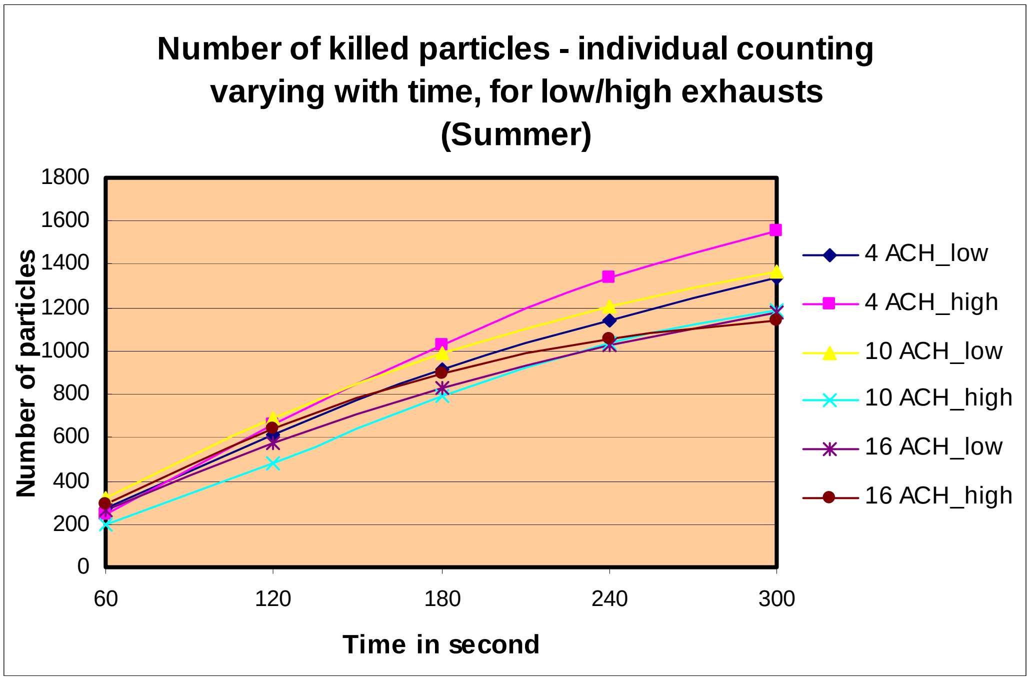


Figure 5.41. *Number of killed particles - individual counting - with exhaust location change (Summer)*

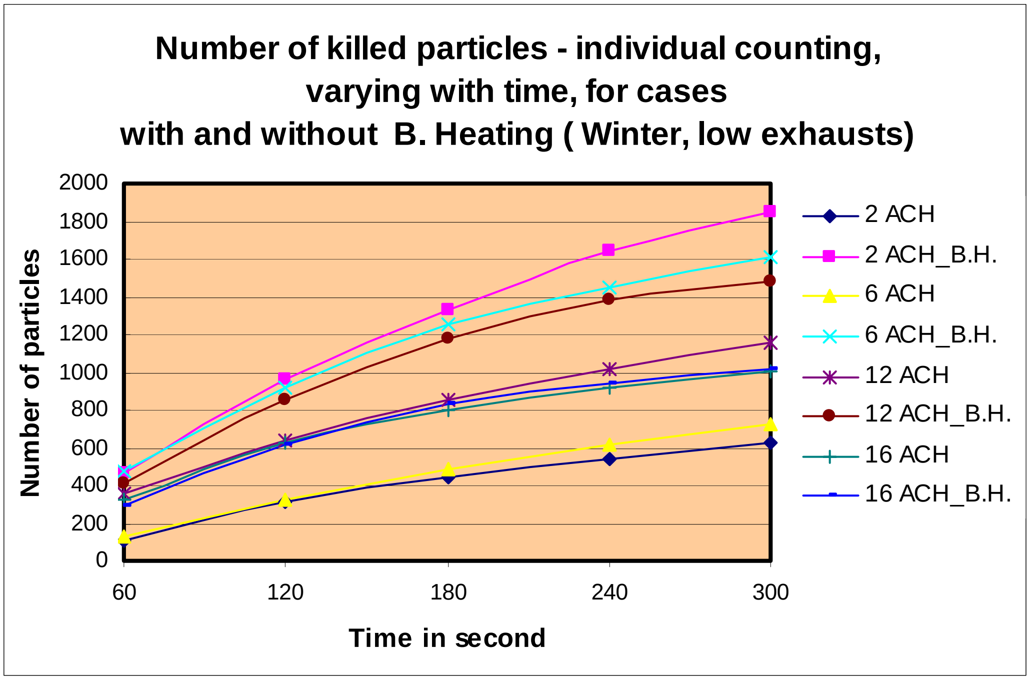


***Figure* 5.42.** *Number of killed particles - individual counting- for cases with/without Baseboard Heating*

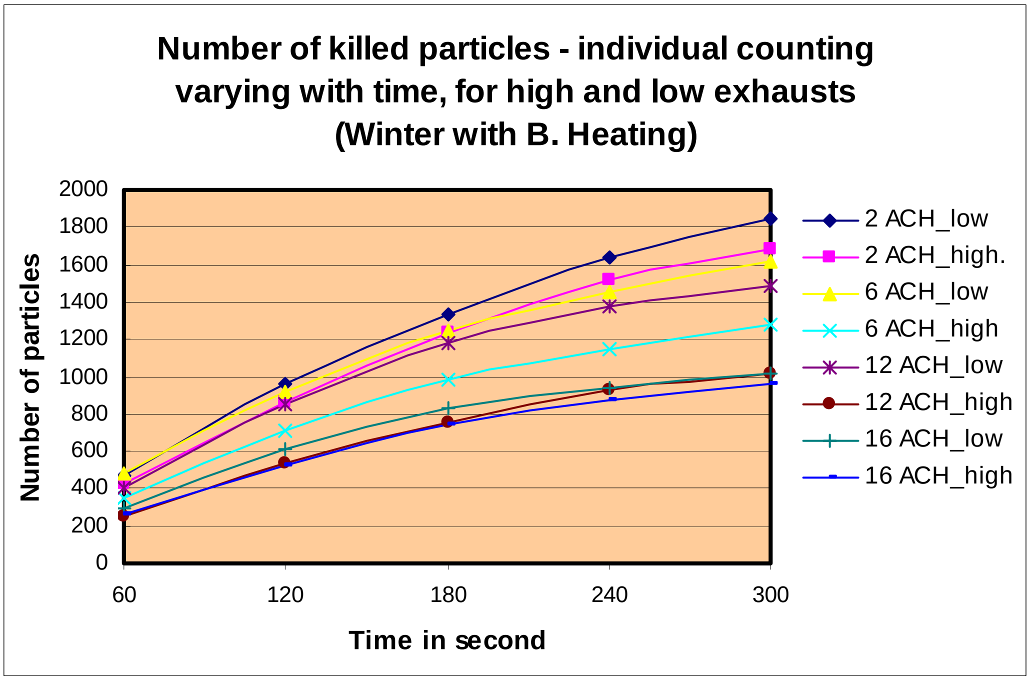


***Figure* 5.43.** *Number of killed particles - individual counting - for exhaust location change when baseboard heating is applied*

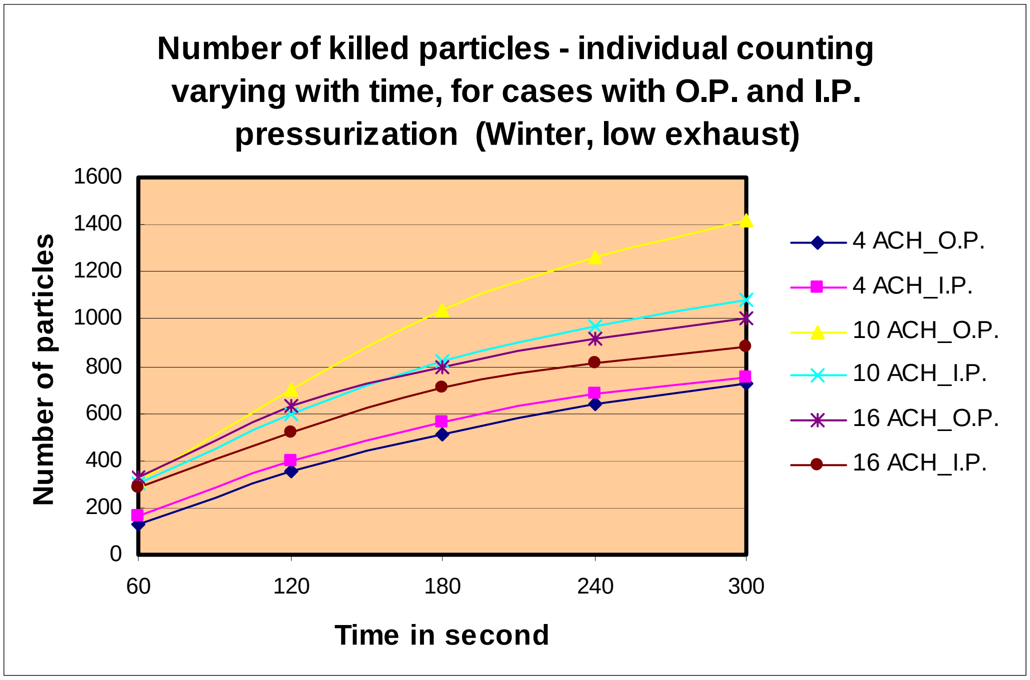


Figure 5.44. *Number of killed particles - individual counting - for cases with original / increased pressurization (Winter)*

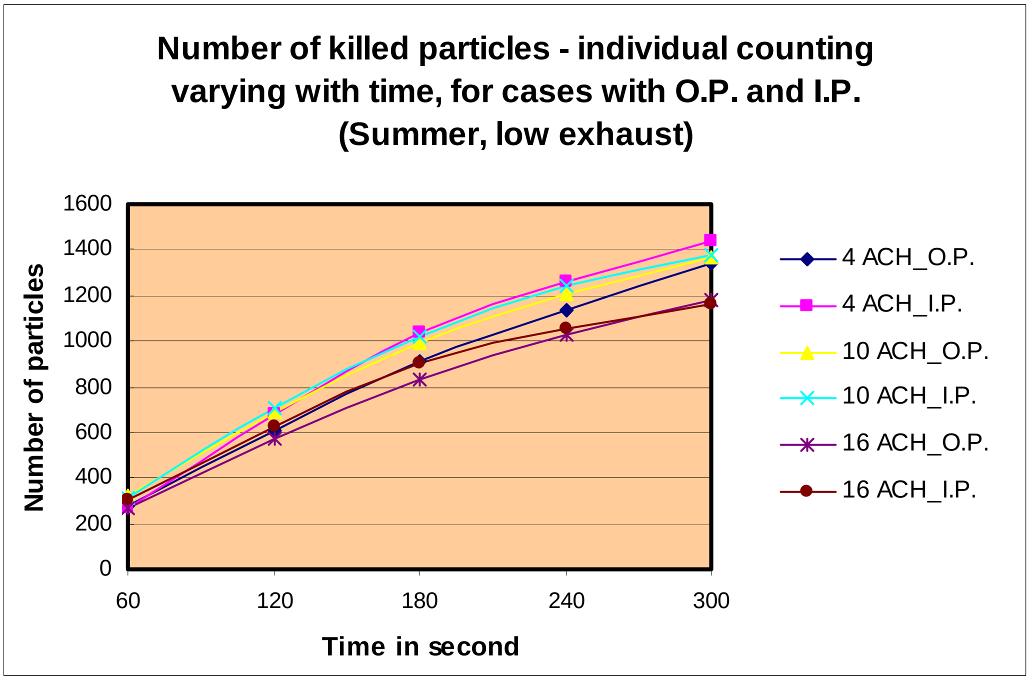


Figure 5.45. *Number of killed particles - individual counting - for cases with original / increased pressurization (Summer)*

5.3.6 The Survival Fraction of Particles –Group Counting - Varying with Time (UV1)

UV1: UVGI output power 10W, located on the partition wall, 7.5’ from the floor.

For winter cases, the survival fractions at the end of 300s fall between 85-95% for all ventilation flow rates. The 10 ACH case shows the lowest surviving fraction. Higher values of ACH show decreasing benefits (See Figure 5.46). For summer cases, the survival fraction is generally less sensitive to the flow rate than winter condition. For the summer cases with peak load, the surviving fractions are generally lower that those for winter cases as shown in Figure 5.48.

In comparison of high and low exhausts, high exhausts results slightly lower surviving fractions at summer condition (See Figure 5.50).

Figure 5.51 indicates that baseboard heating significantly reduces surviving fractions for entire range of flow rate. Figure 5.52 compares the high and low exhausts with baseboard heating used, which shows that low exhausts generally result in lower surviving fraction.

Increased pressurization of the room in winter condition increases the surviving as indicated in Figure 5.53. The same is applied to summer cases, as shown in Figure 5.54.

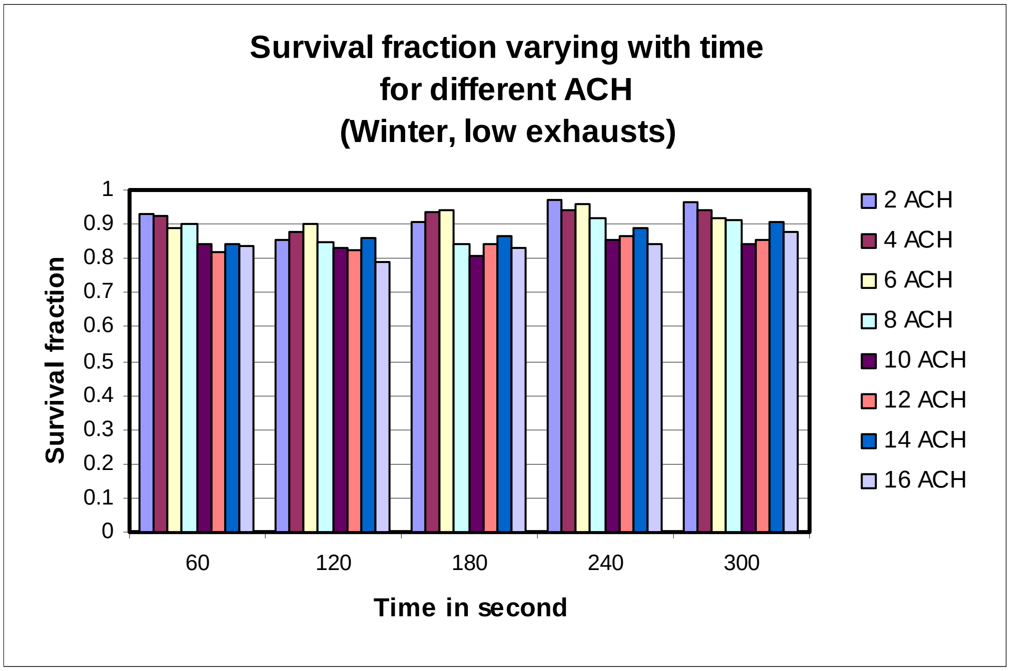


Figure 5.46. *Survival fraction with ACH change (Winter)*

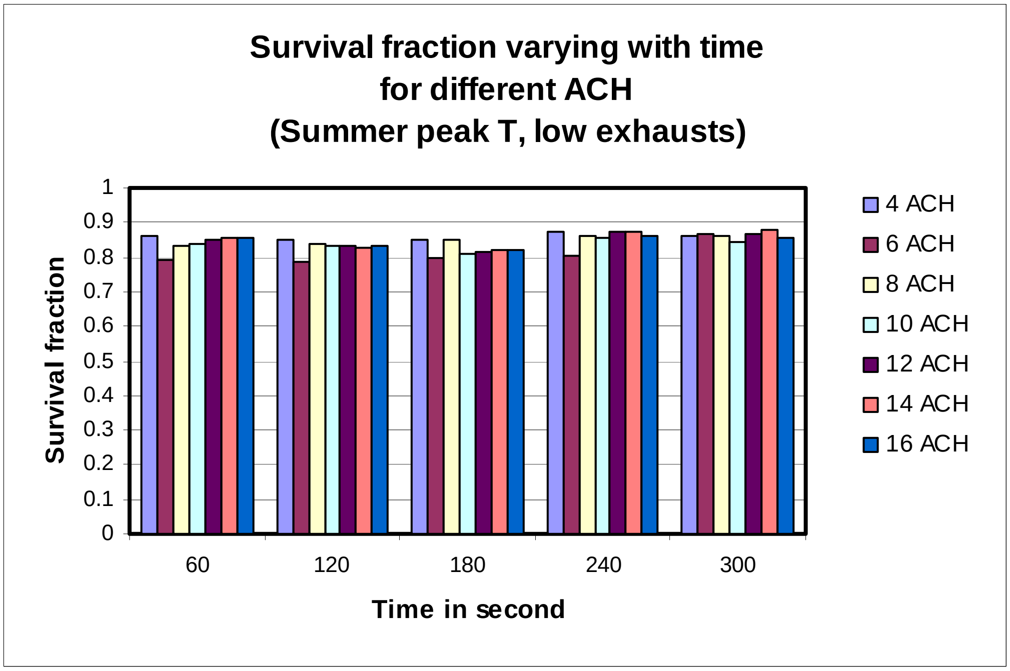


Figure 5.47. *Survival fraction with ACH change (Summer)*

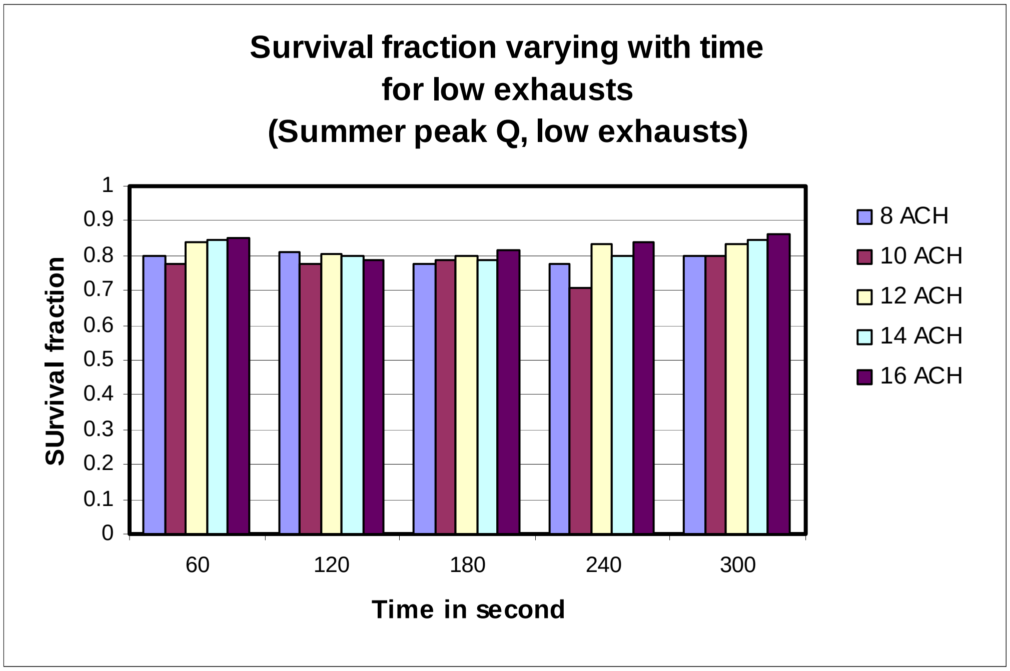


Figure 5.48. *Survival fraction with ACH change (Summer)*

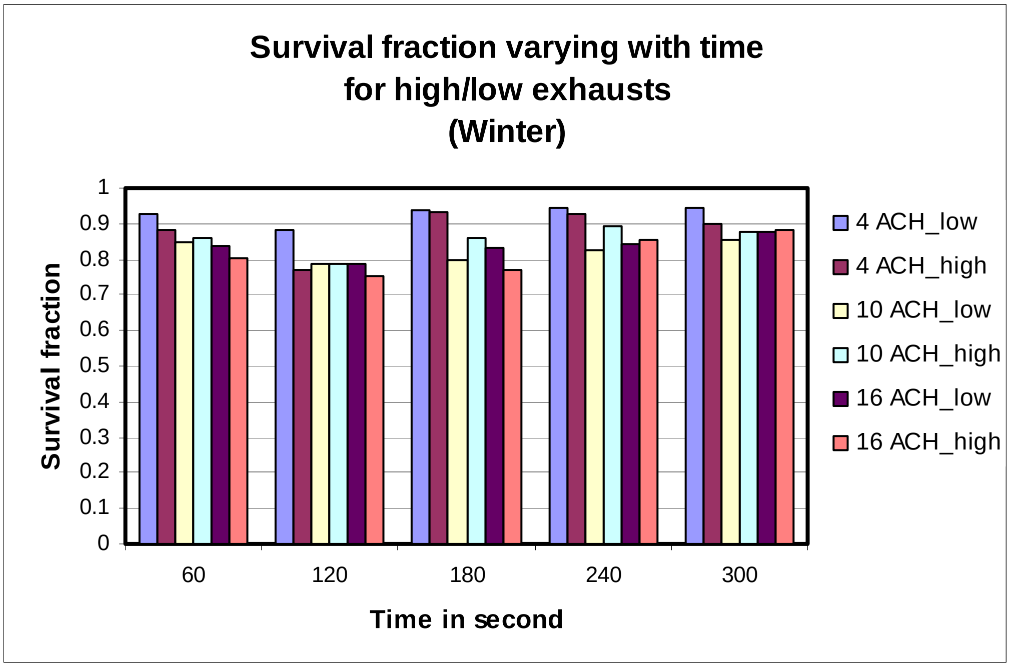


Figure 5.49. *Survival fraction with exhaust location change (Winter)*

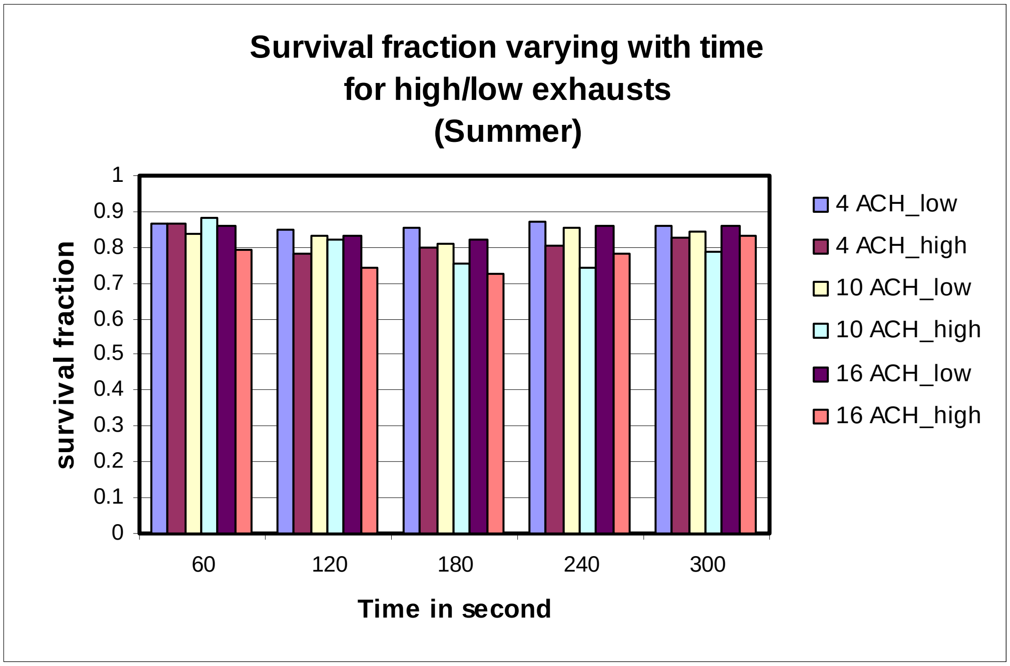


Figure 5.50. *Survival fraction with exhaust location change (Summer)*

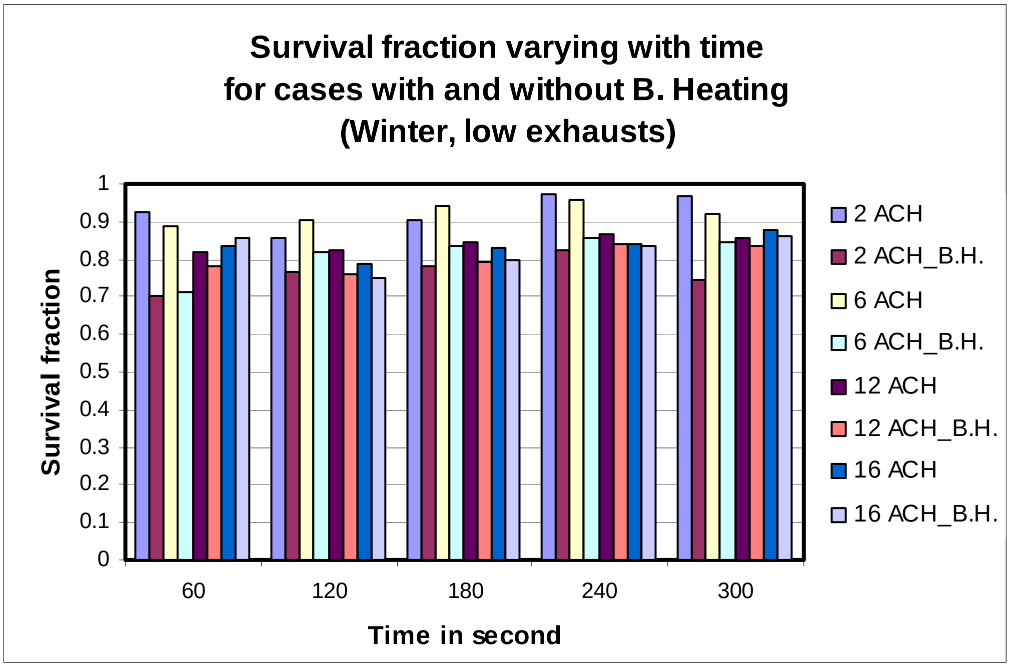


Figure 5.51. *Survival fraction for cases with/without Baseboard Heating*

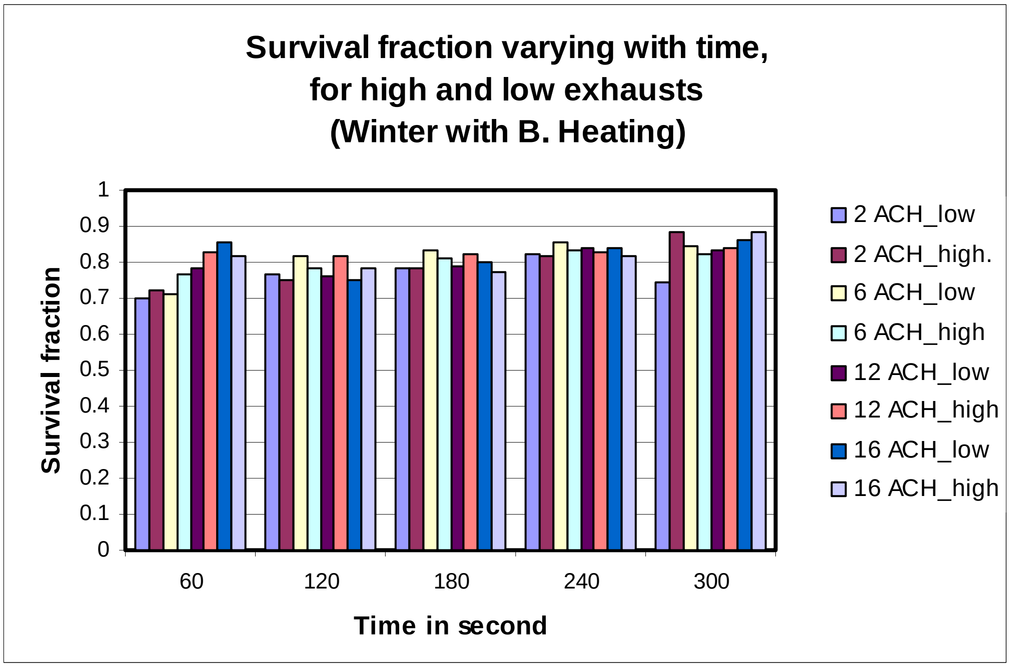


Figure 5.52. *Survival fraction for exhaust location change when baseboard heating is applied*

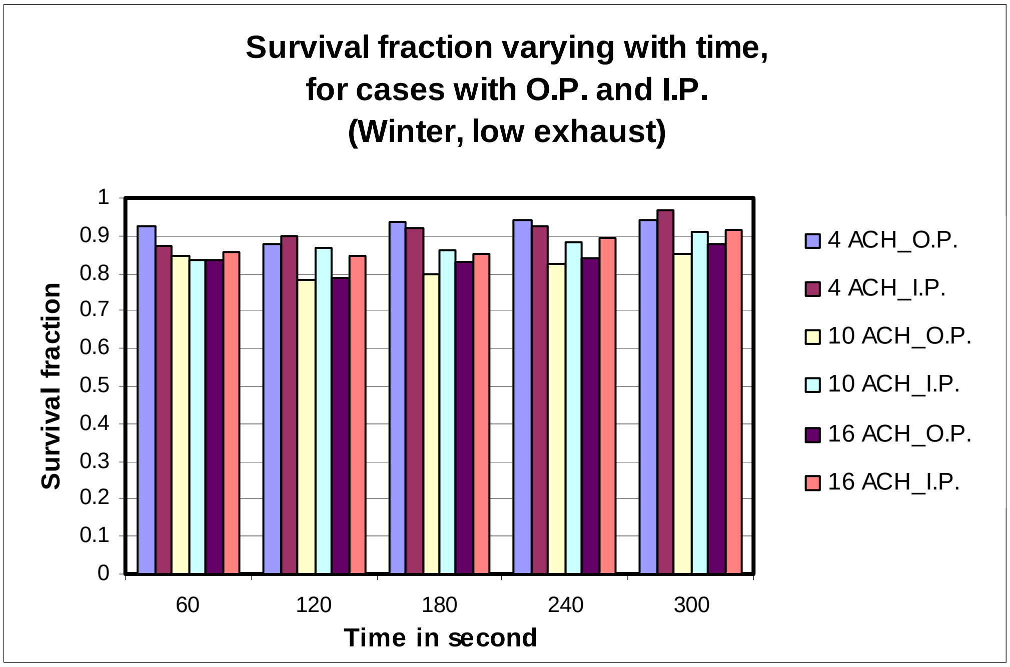


Figure 5.53. *Survival fraction for cases with original/ increased pressurization (Winter)*

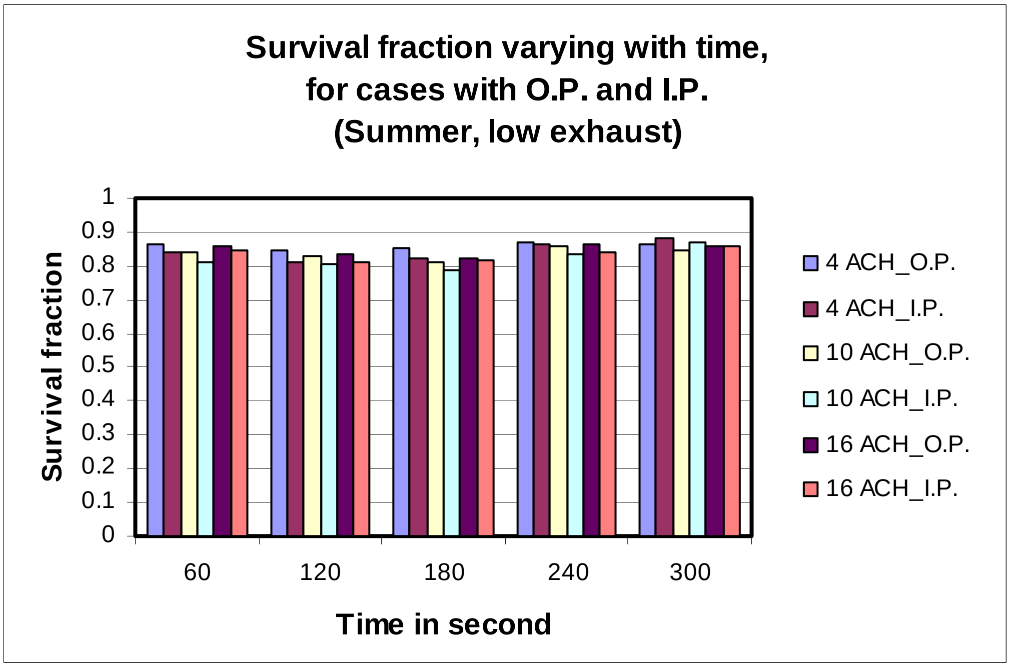


Figure5.54. *Survival fraction for cases with original/ increased pressurization (Summer)*