SECTION V

RESULTS

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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

<u>Note 4:</u>

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.

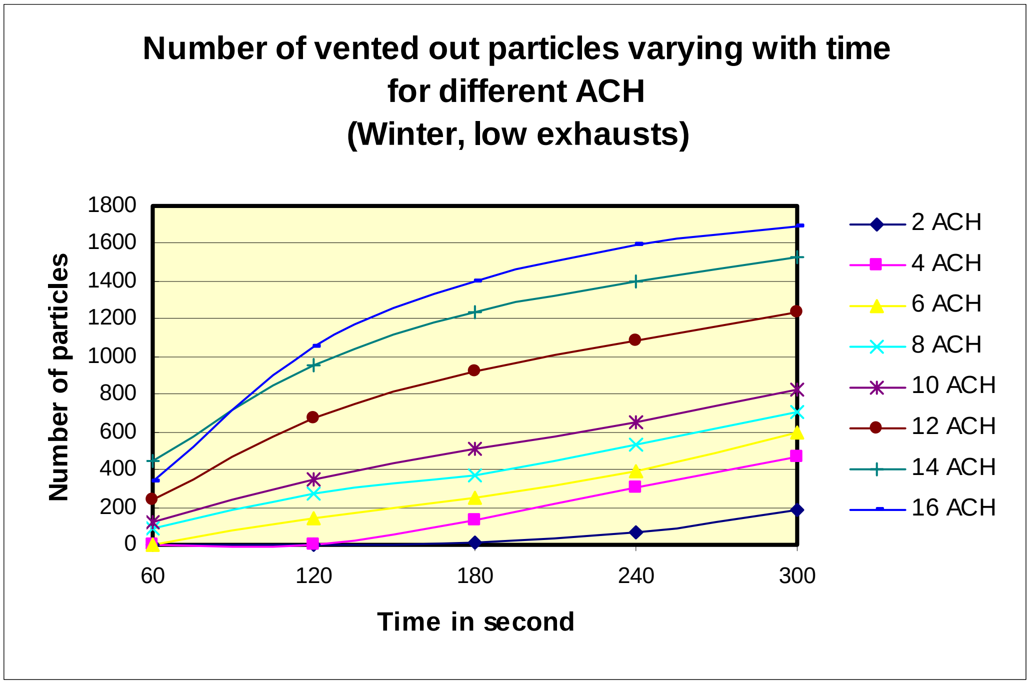

Figure 5.1. *Number of vented out particles with ACH change (Winter)*

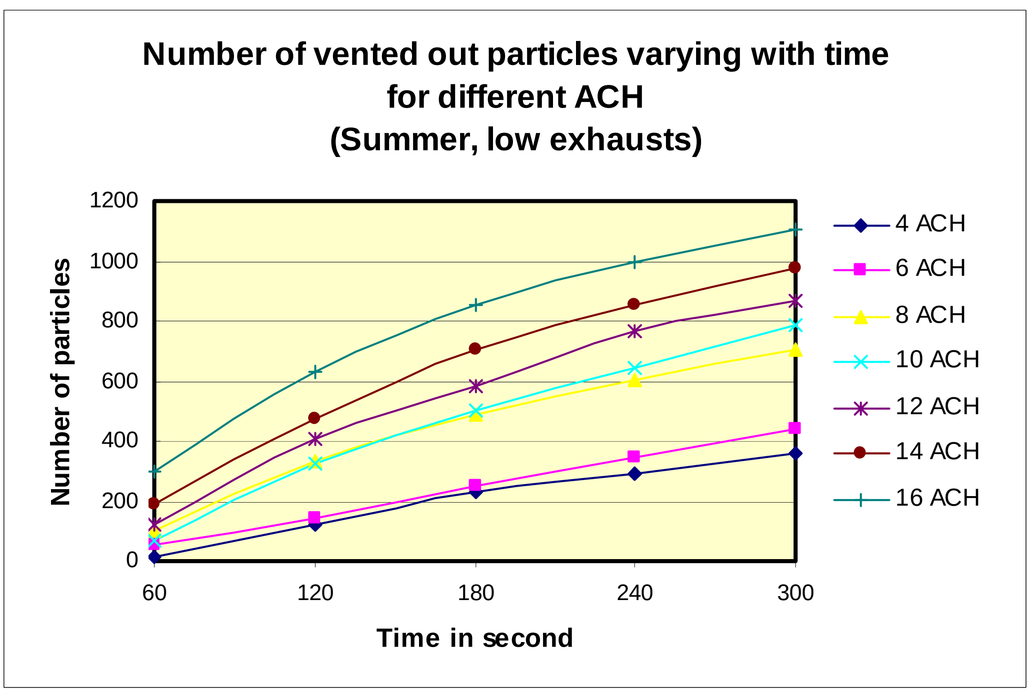

Figure 5.2. *Number of vented out particles with ACH change (Summer)*

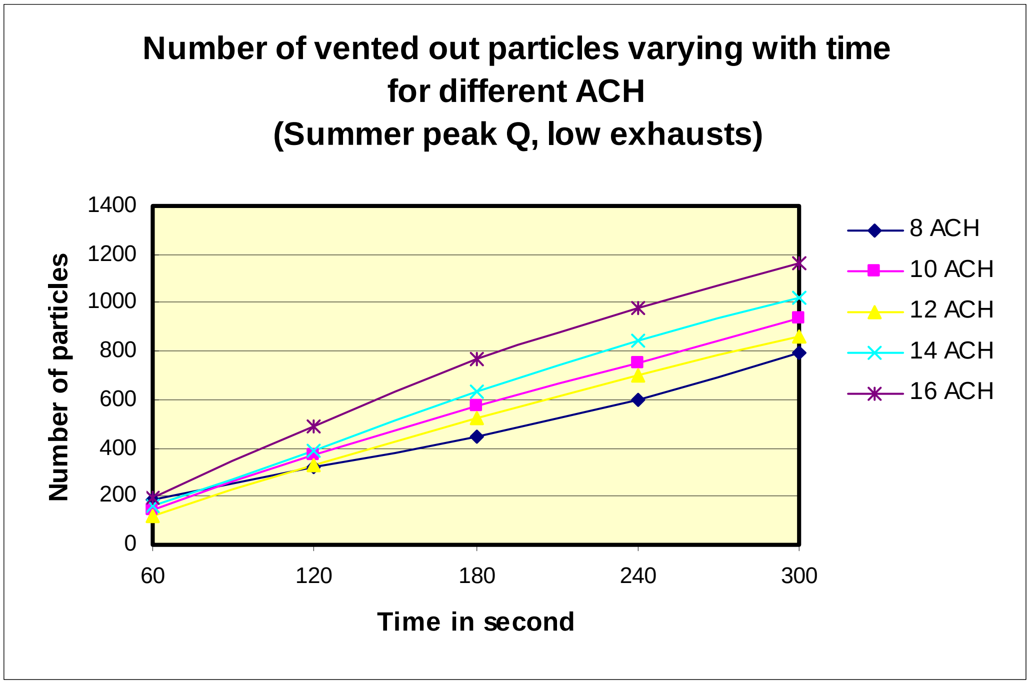

Figure 5.3. *Number of vented out particles with ACH change (Summer peak Q)*

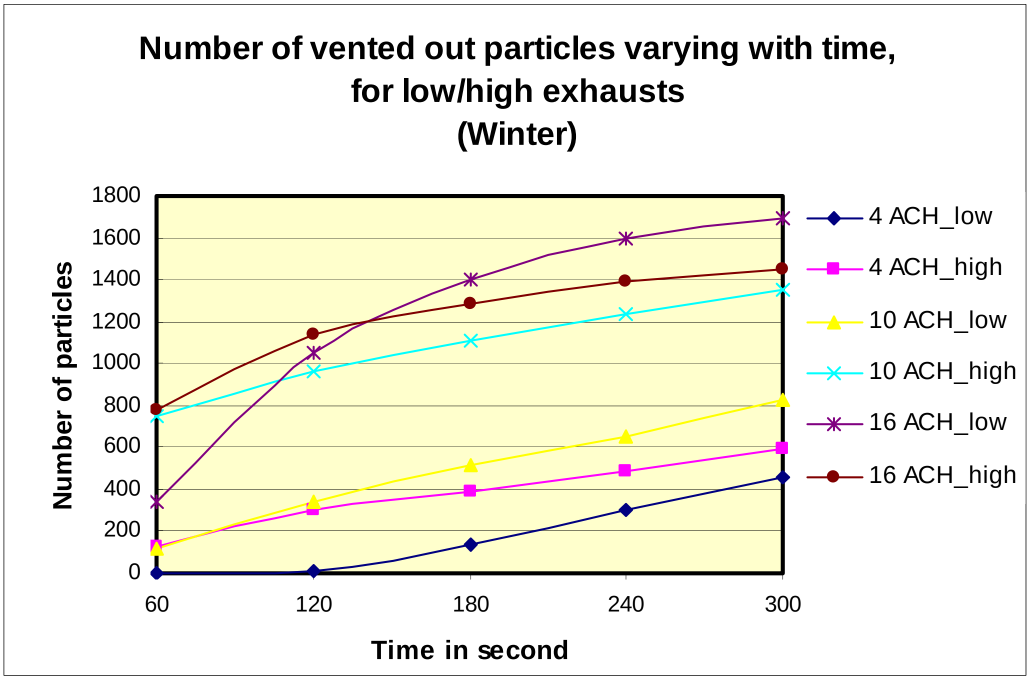

Figure 5.4. *Number of vented out particles with exhaust location change (Winter)*

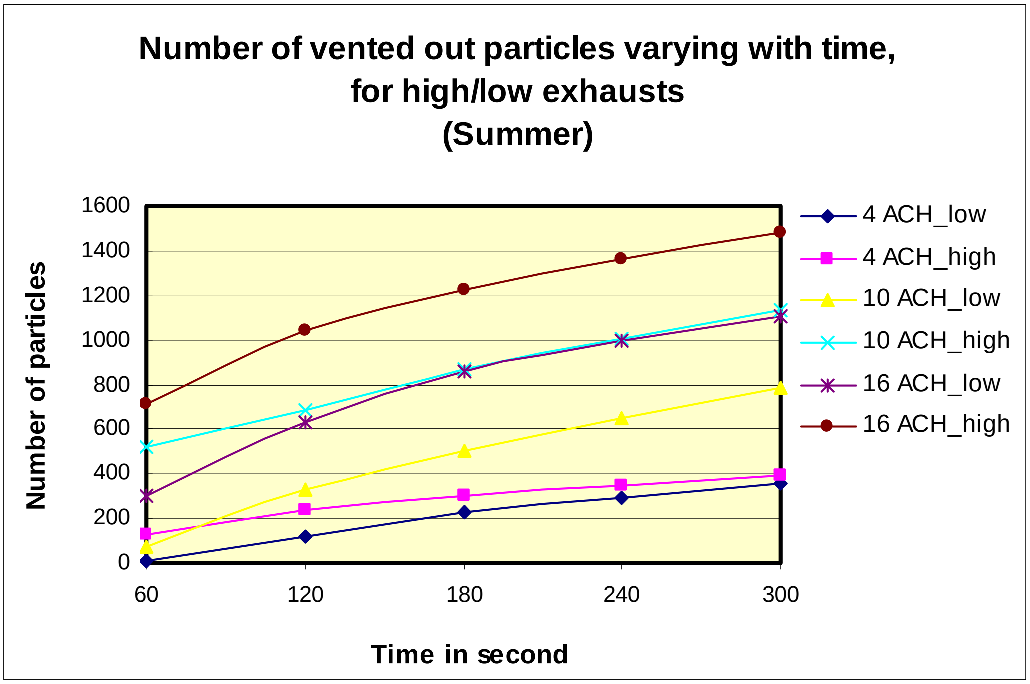

Figure 5.5. *Number of vented out particles with exhaust location change (Summer)*

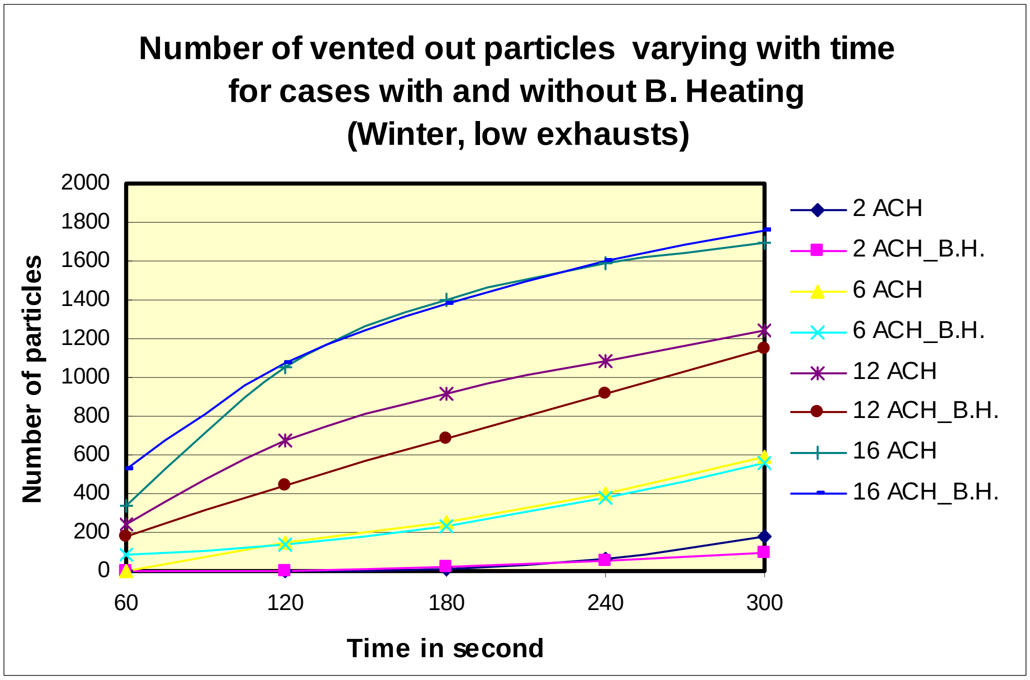

Figure 5.6. *Number of vented out particles for cases with/without Baseboard Heating*

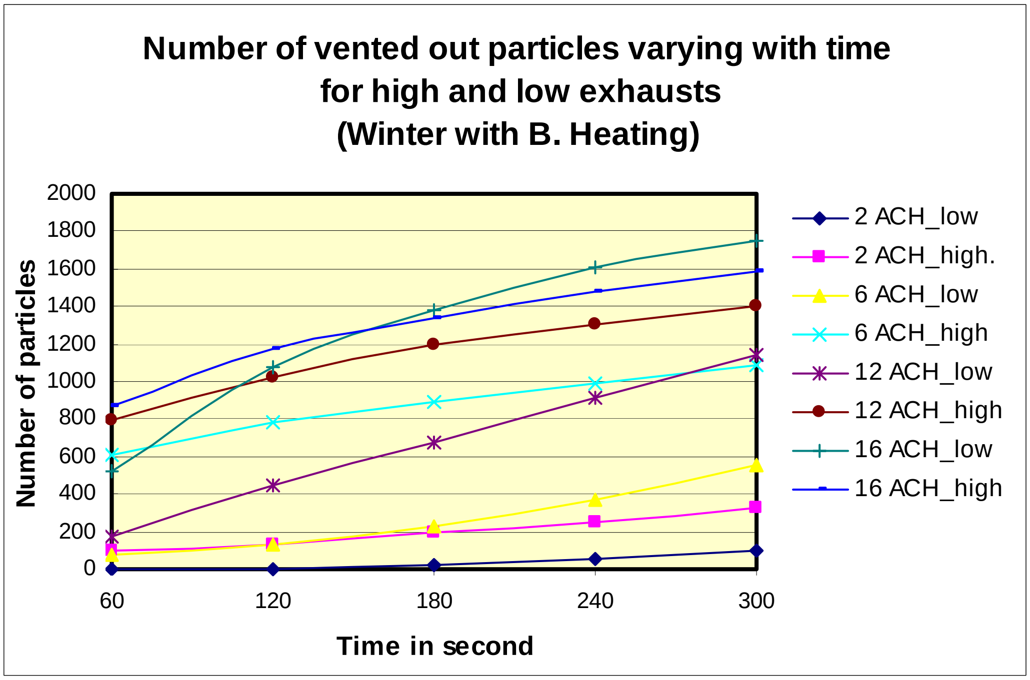

Figure 5.7. *Number of vented out particles for exhaust location change when baseboard heating is applied*

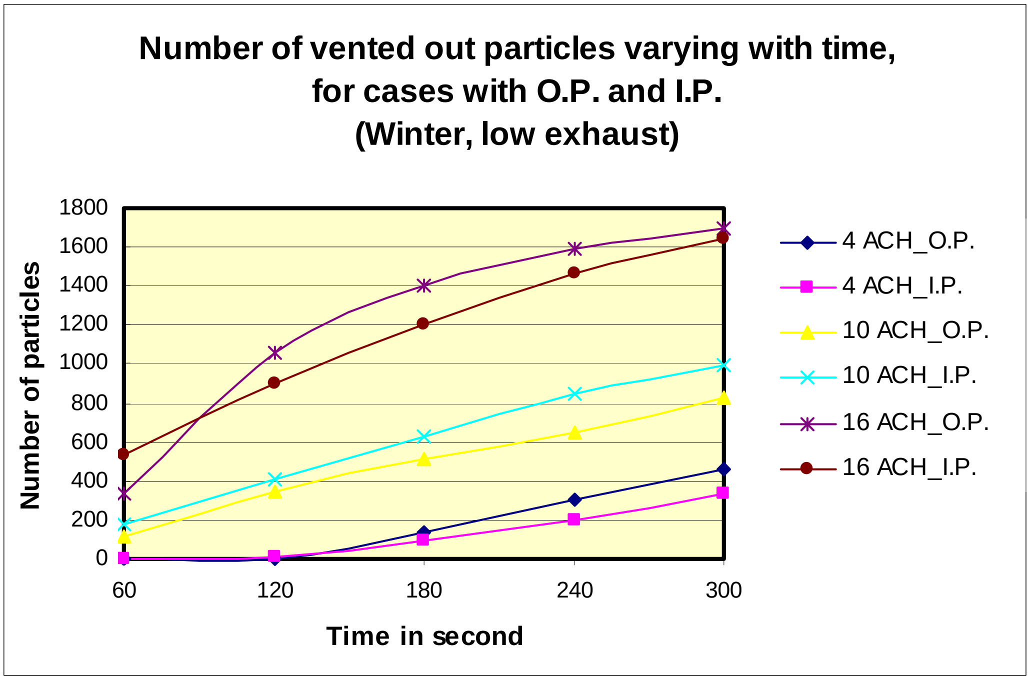

Figure 5.8. *Number of vented out particles for cases with original/ increased pressurization (Winter)*

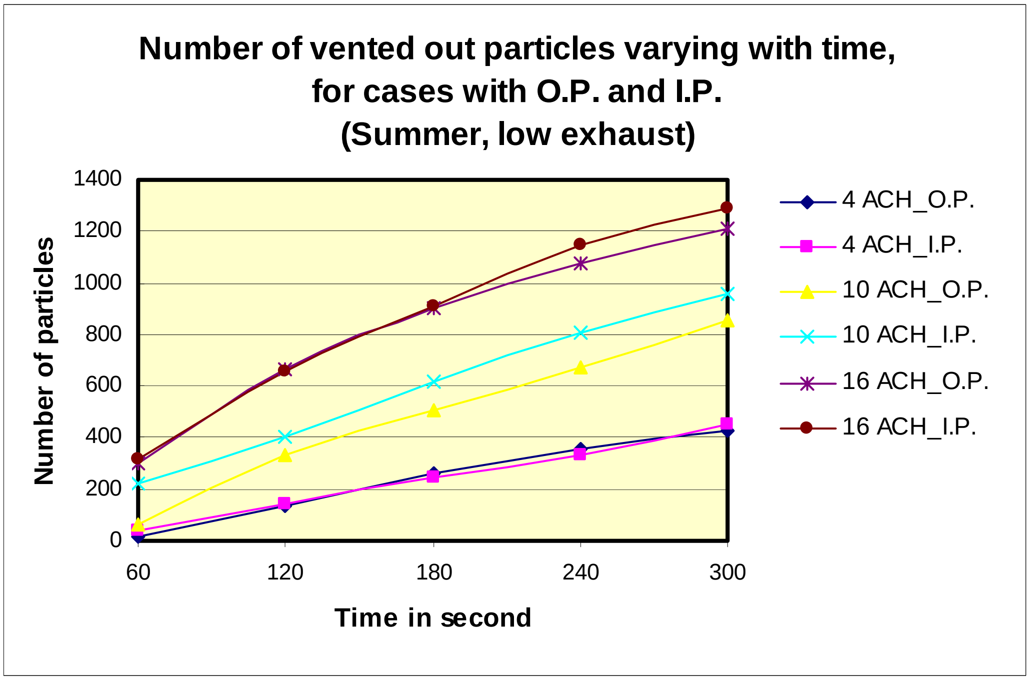

Figure 5.9. *Number of vented out particles for cases with original/ increased pressurization (Summer)*

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.

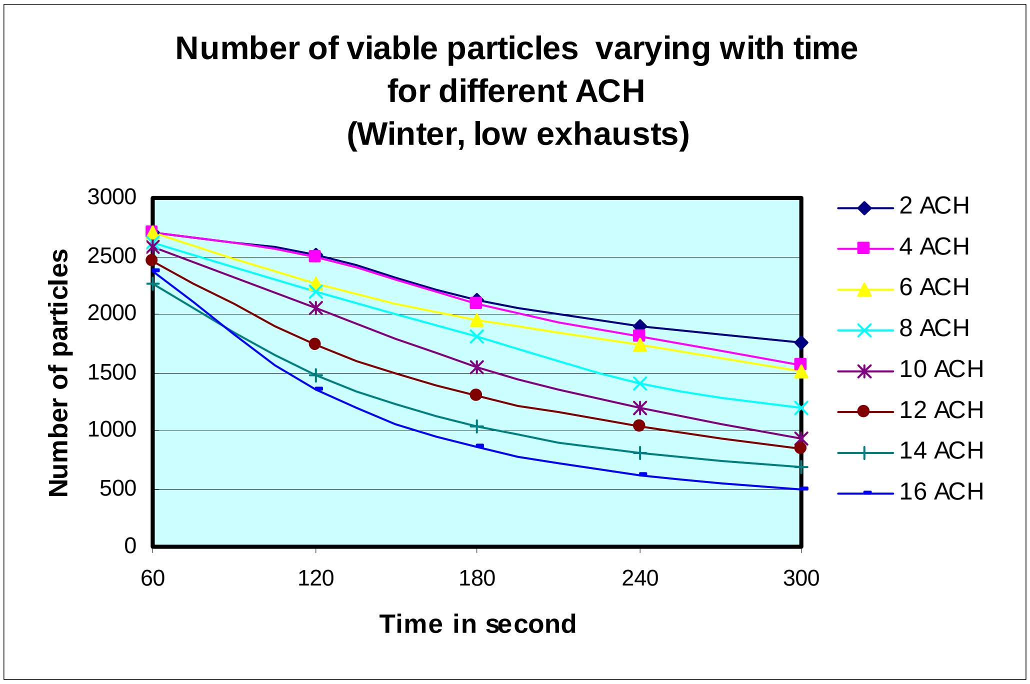

__Figure 5.10.__ Number of viable particles with ACH change (Winter)

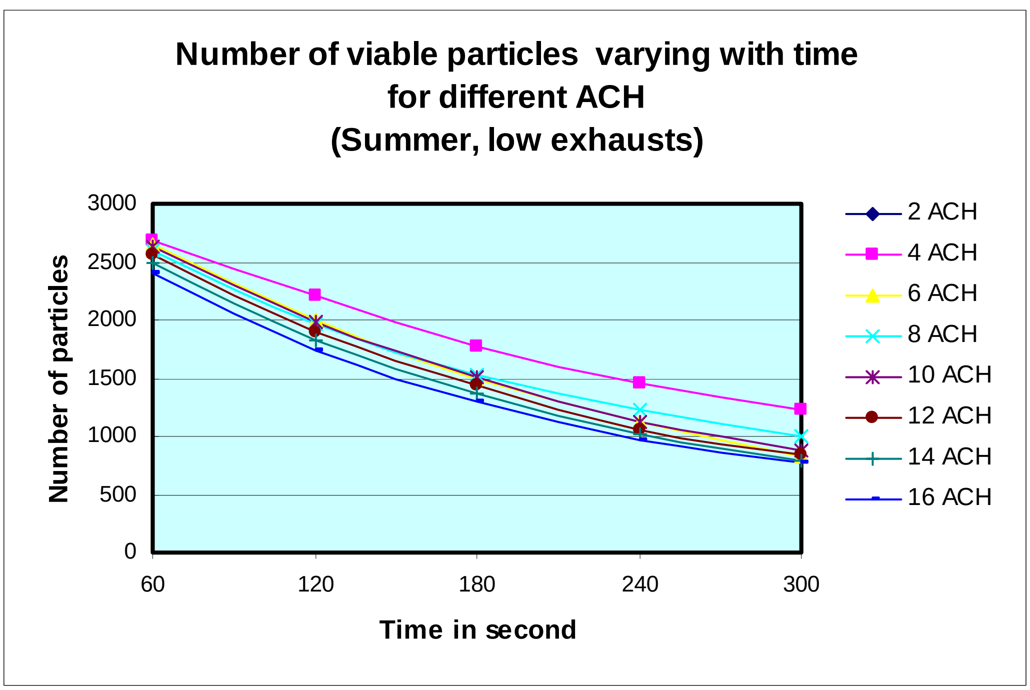

__Figure 5.11.__ Number of viable particles with ACH change (Summer).

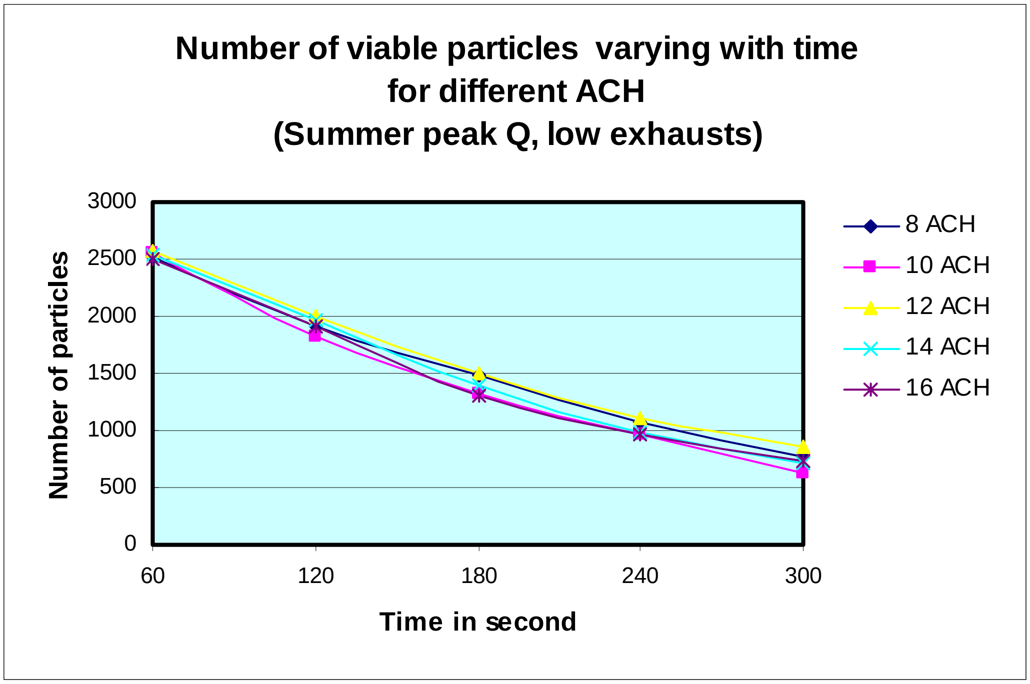

Figure 5.12. *Number of viable particles with ACH change (Summer peak Q).*

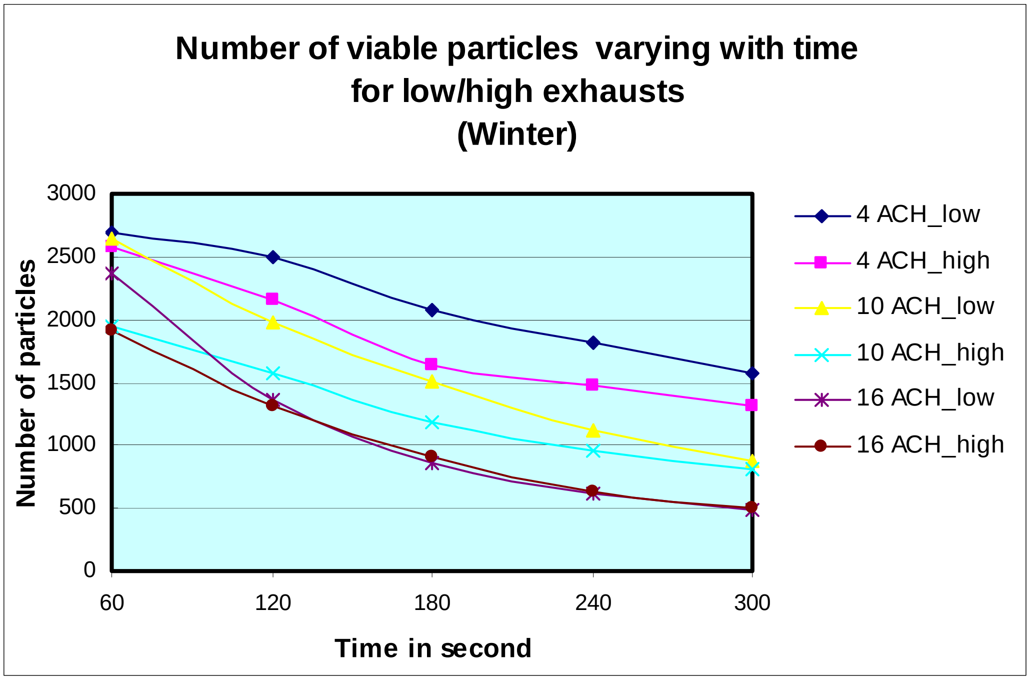

Figure 5.13. *Number of viable particles with exhaust location change (Winter).*

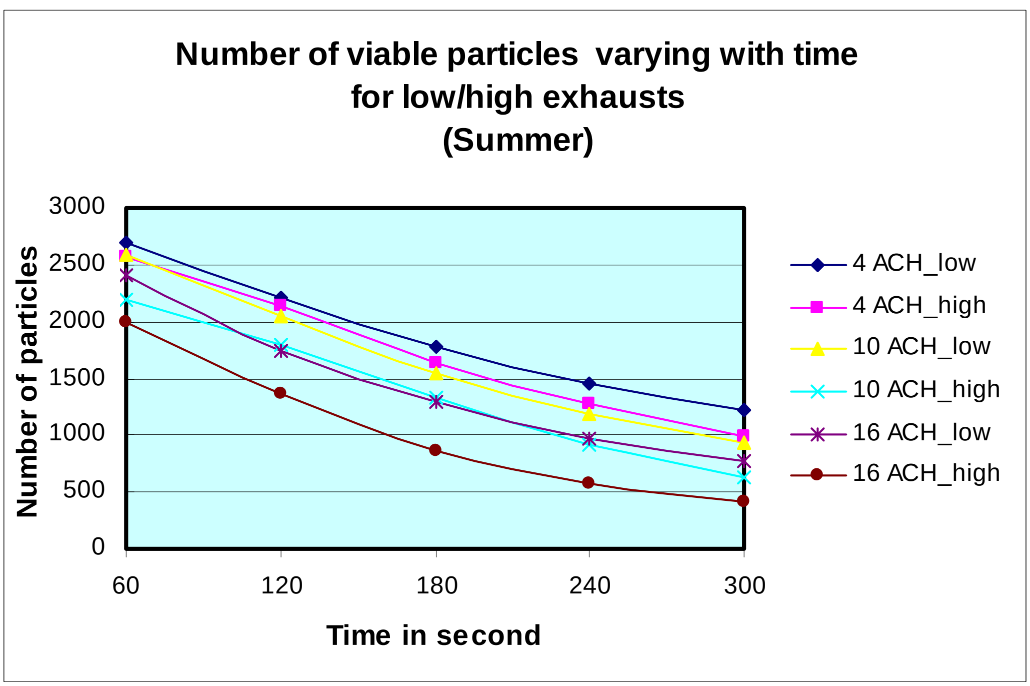

Figure 5.14. *Number of viable particles with exhaust location change (Summer).*

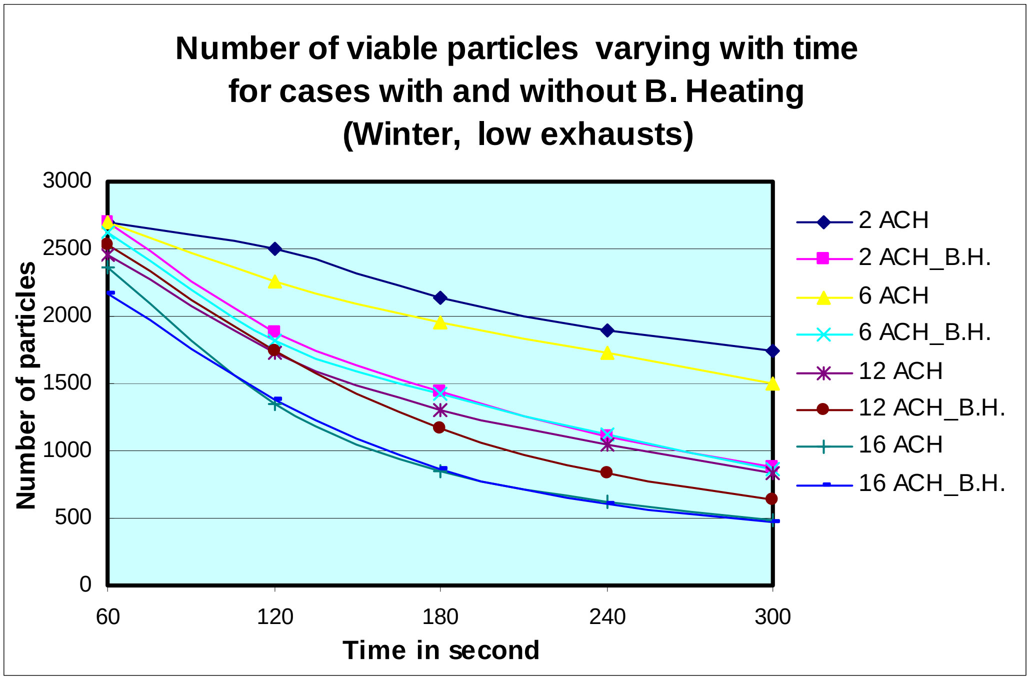

Figure 5.15. *Number of viable particles for cases with/ without Baseboard Heating.*

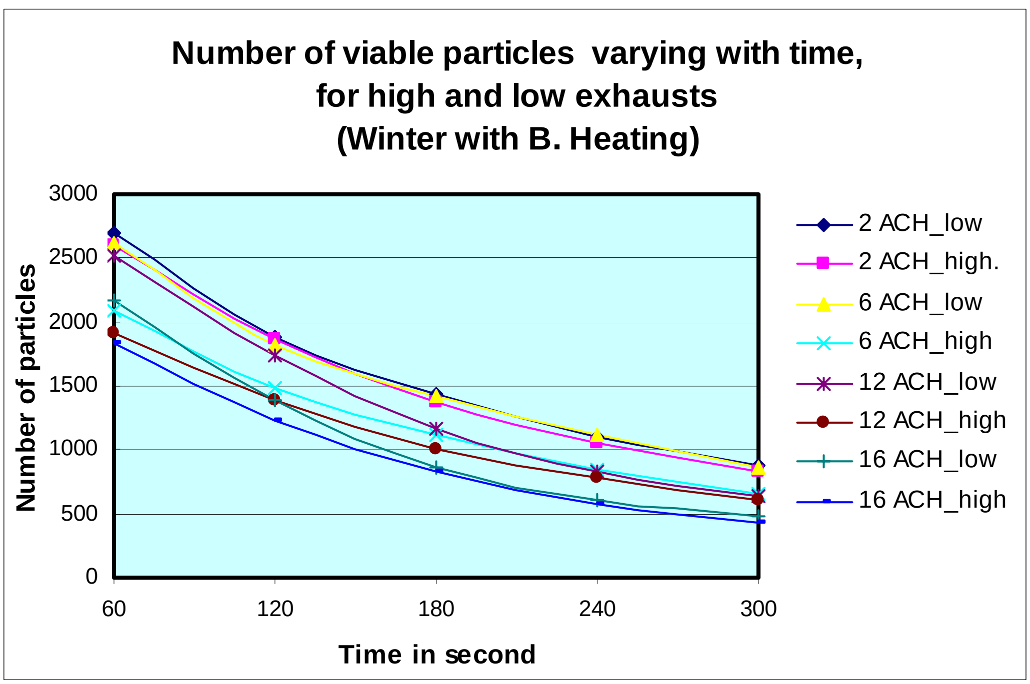

Figure 5.16. *Number of viable particles for exhaust location change when baseboard heating is applied*

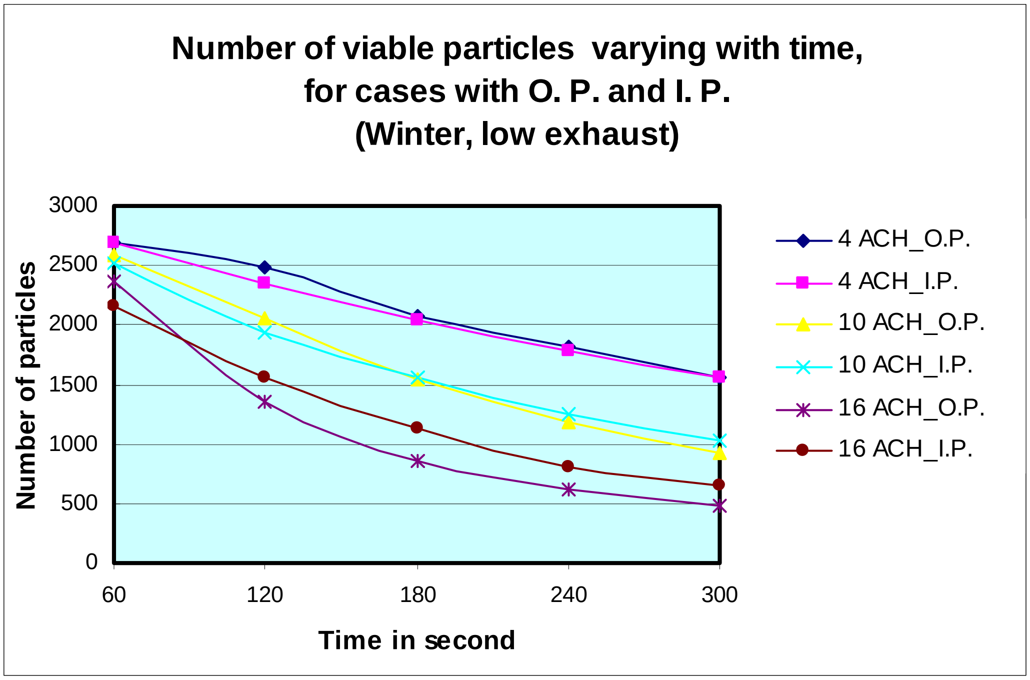

Figure 5.17. *Number of viable particles for cases with original/ increased pressurization (Winter)*

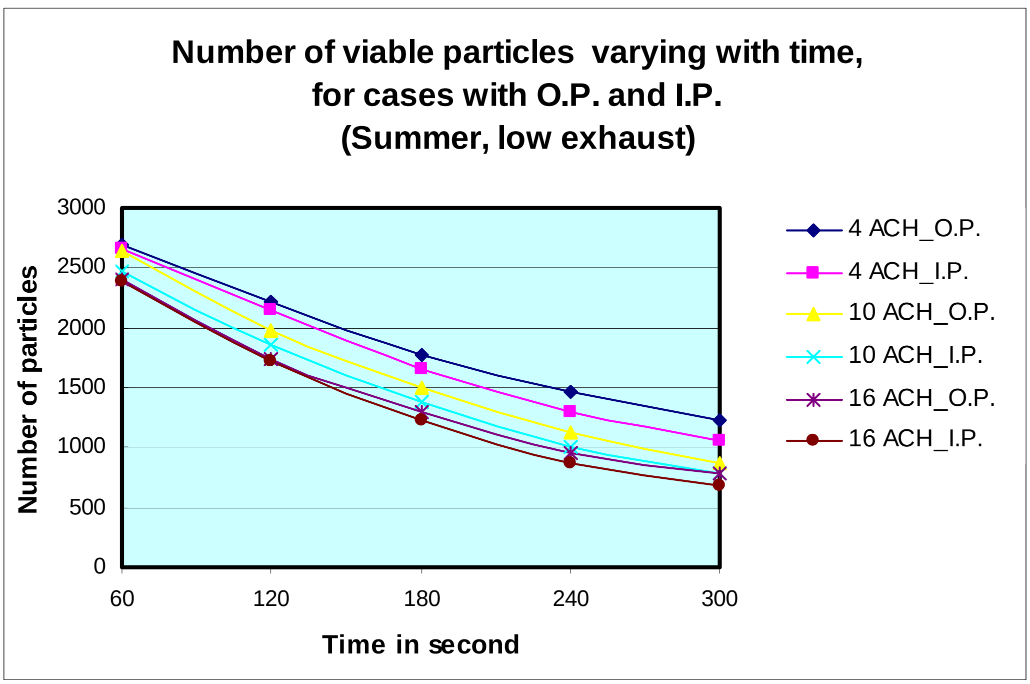

Figure 5.18. *Number of viable particles for cases with original/ increased pressurization (Summer)*

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.

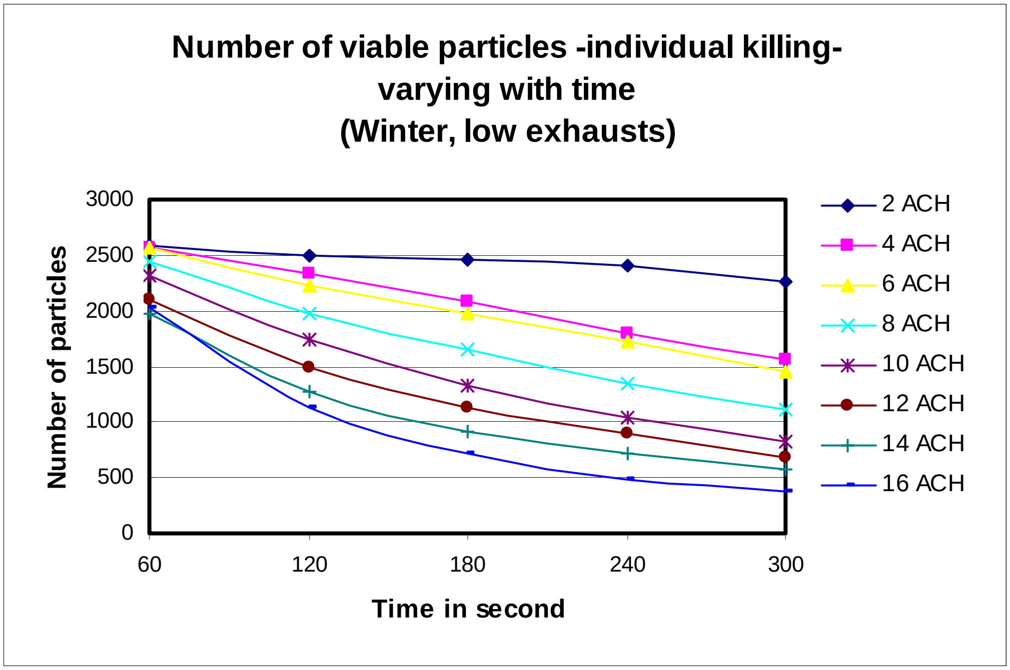

Figure 5.19. *Number of viable particles with ACH change (Winter)*

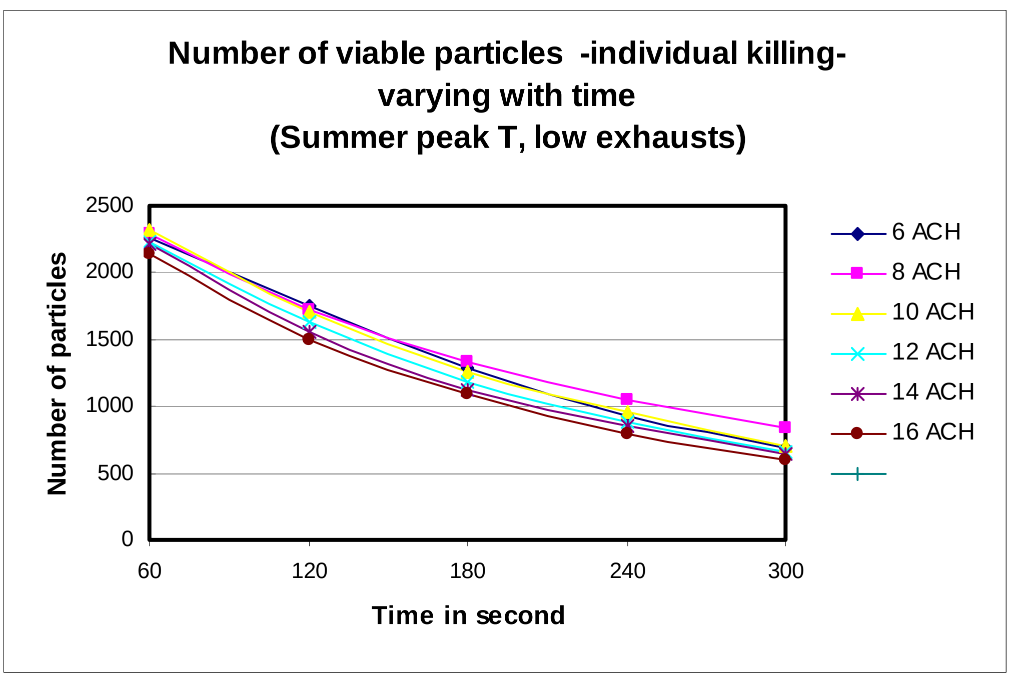

Figure 5.20. *Number of viable particles with ACH change (Summer).*

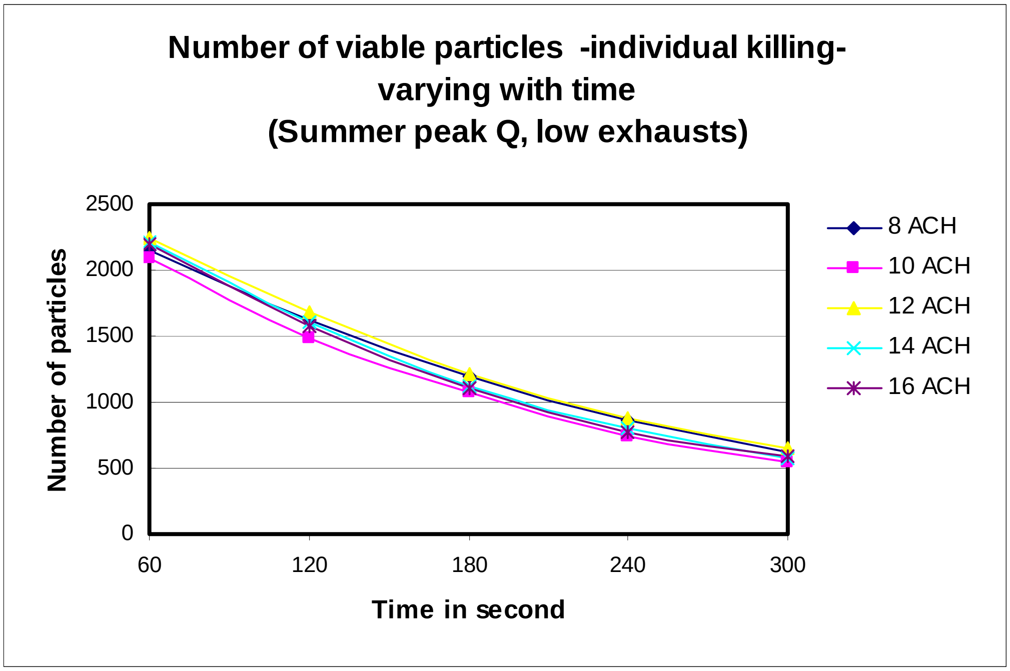

Figure 5.21. *Number of viable particles with ACH change (Summer peak Q).*

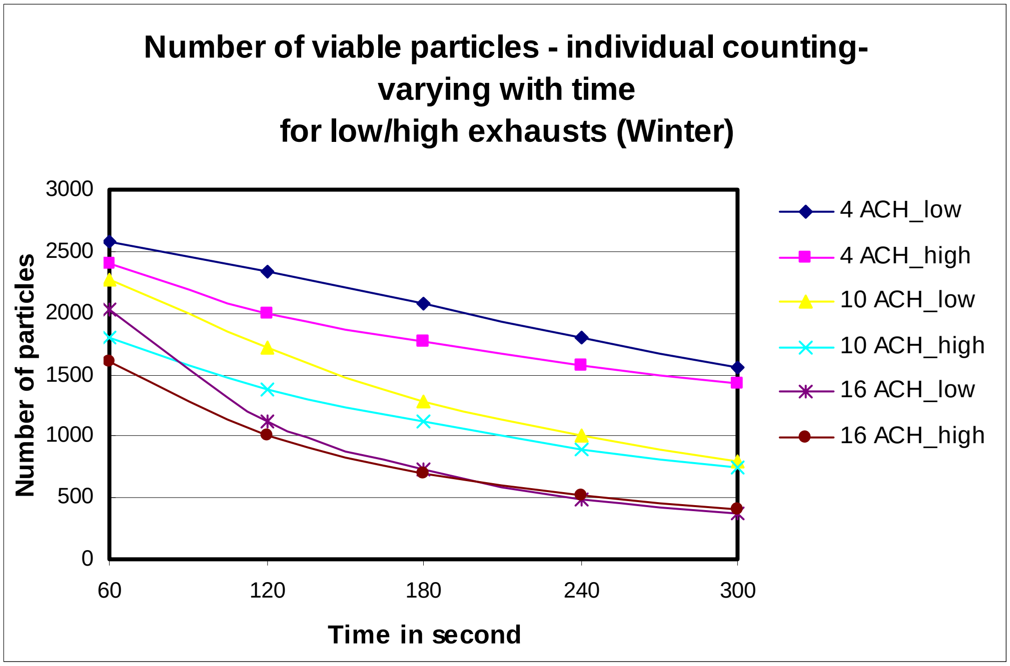

Figure 5.22. *Number of viable particles with exhaust location change (Winter).*

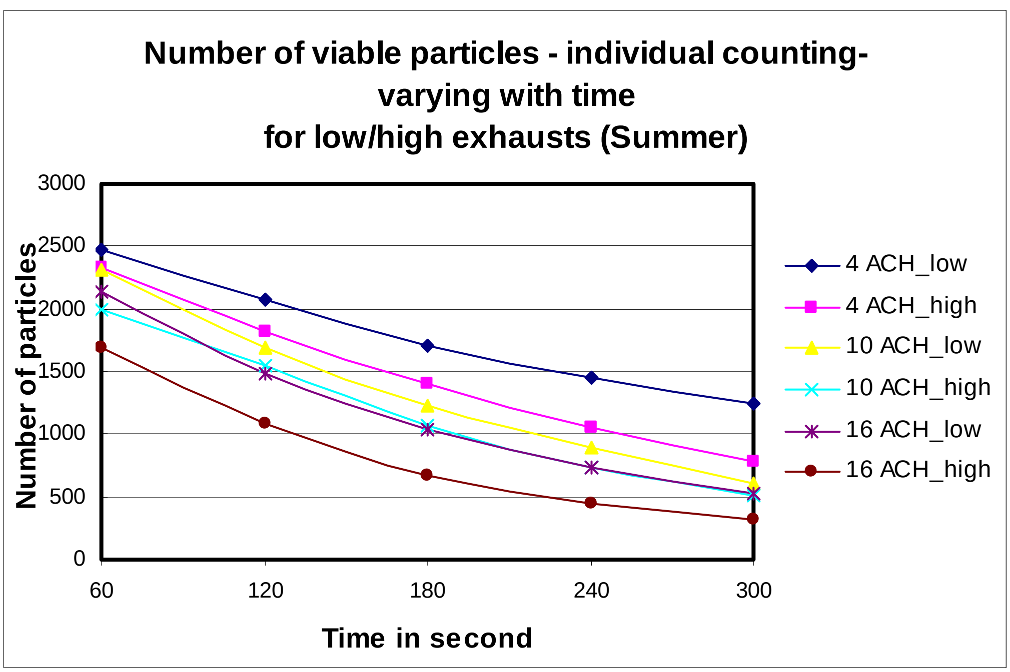

Figure 5.23. *Number of viable particles with exhaust location change (Summer).*

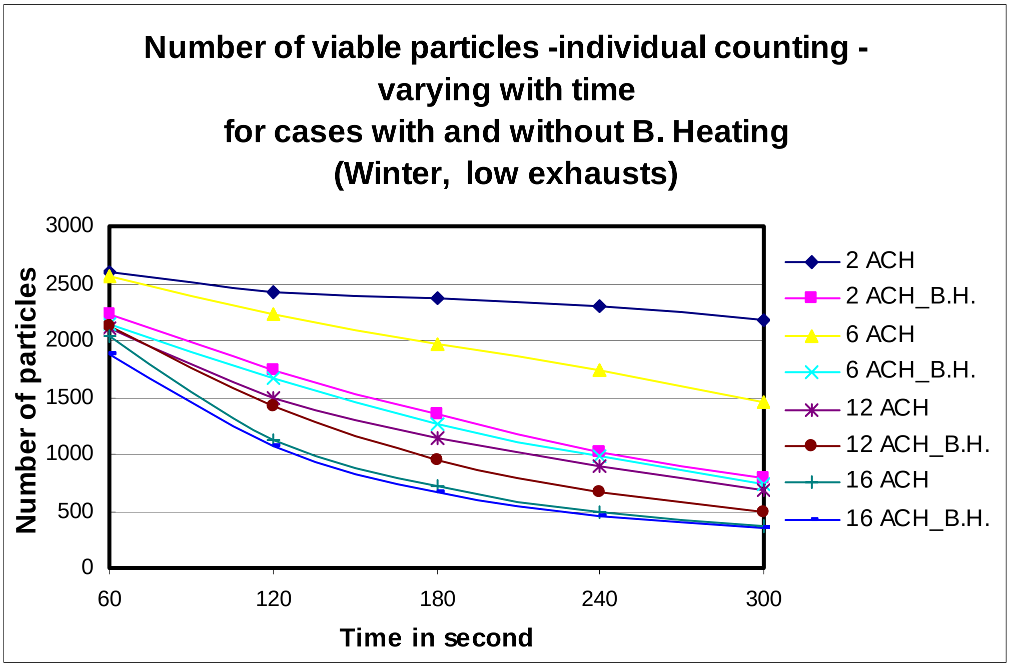

Figure 5.24. *Number of viable particles for cases with/ without Baseboard Heating.*

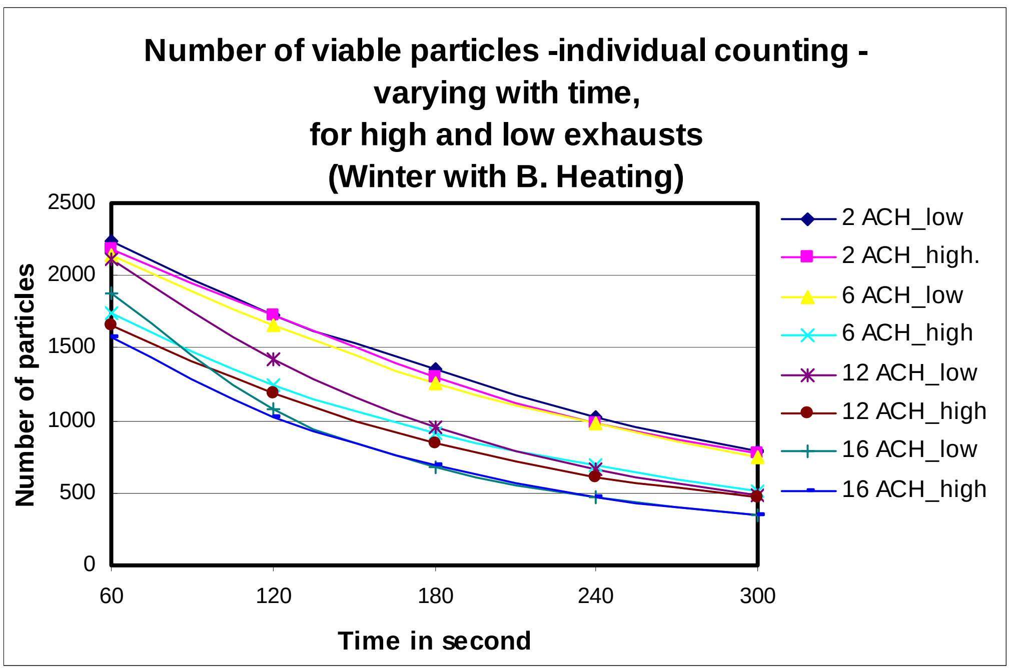

Figure 5.25. *Number of viable particles for exhaust location change when baseboard heating is applied*

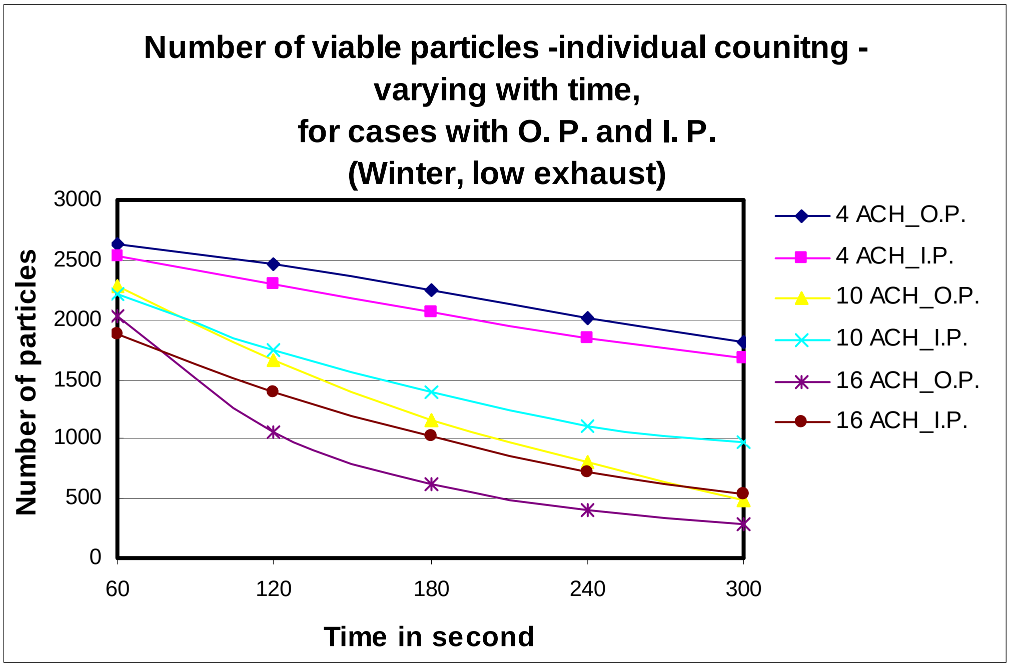

Figure 5.26. *Number of viable particles for cases with original/ increased pressurization (Winter)*

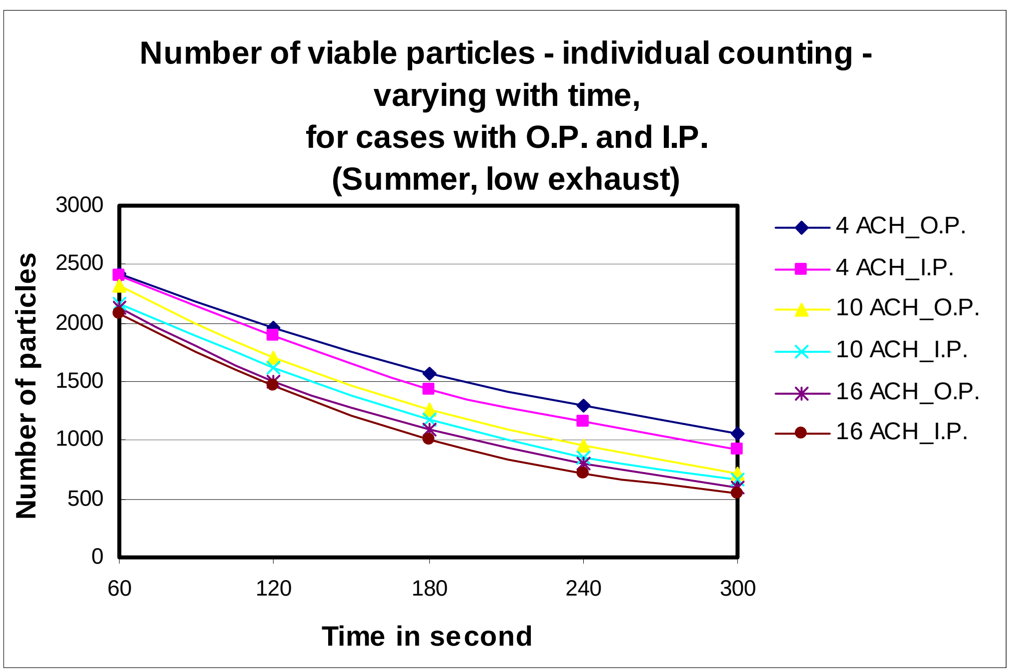

Figure 5.27. *Number of viable particles for cases with original/ increased pressurization (Summer)*

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.

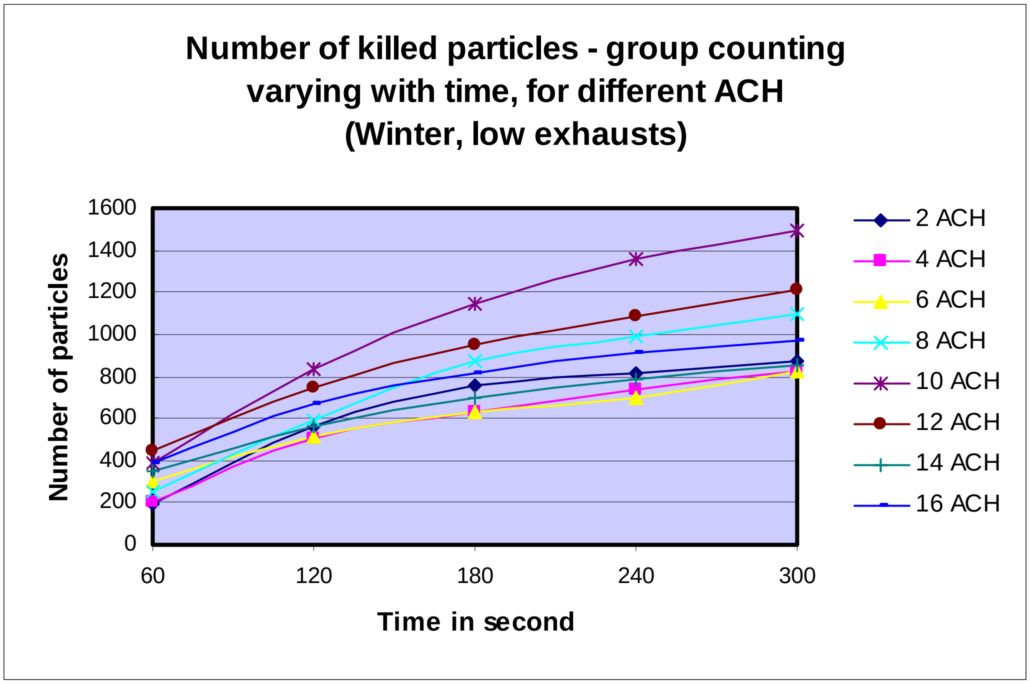

Figure 5.28. *Number of killed particles with ACH change (Winter)*

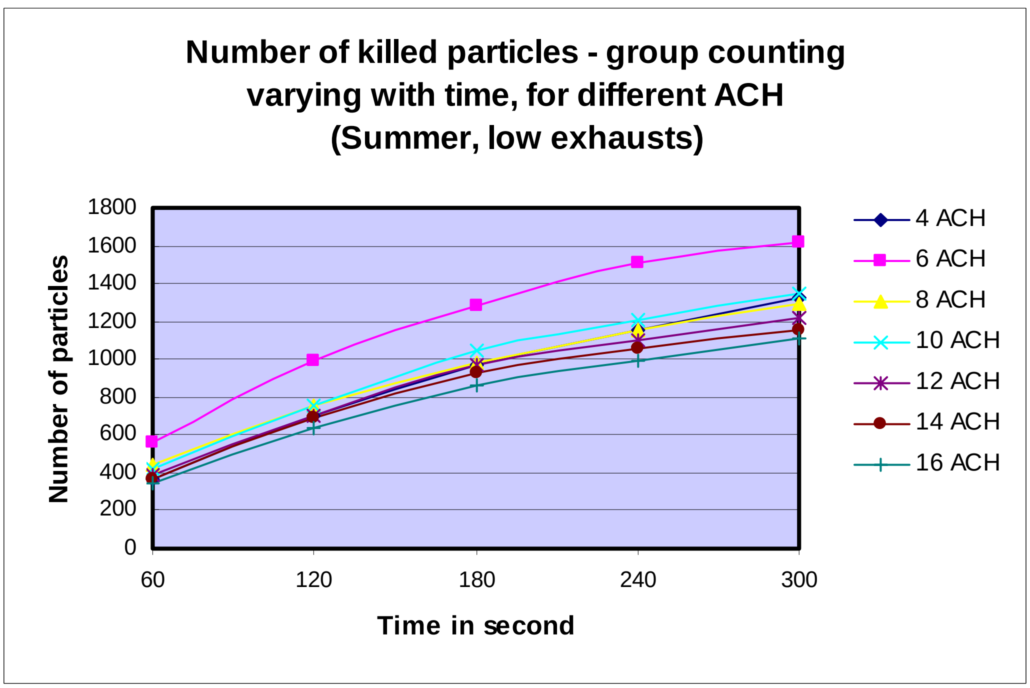

Figure 5.29. *Number of killed particles with ACH change (Summer)*

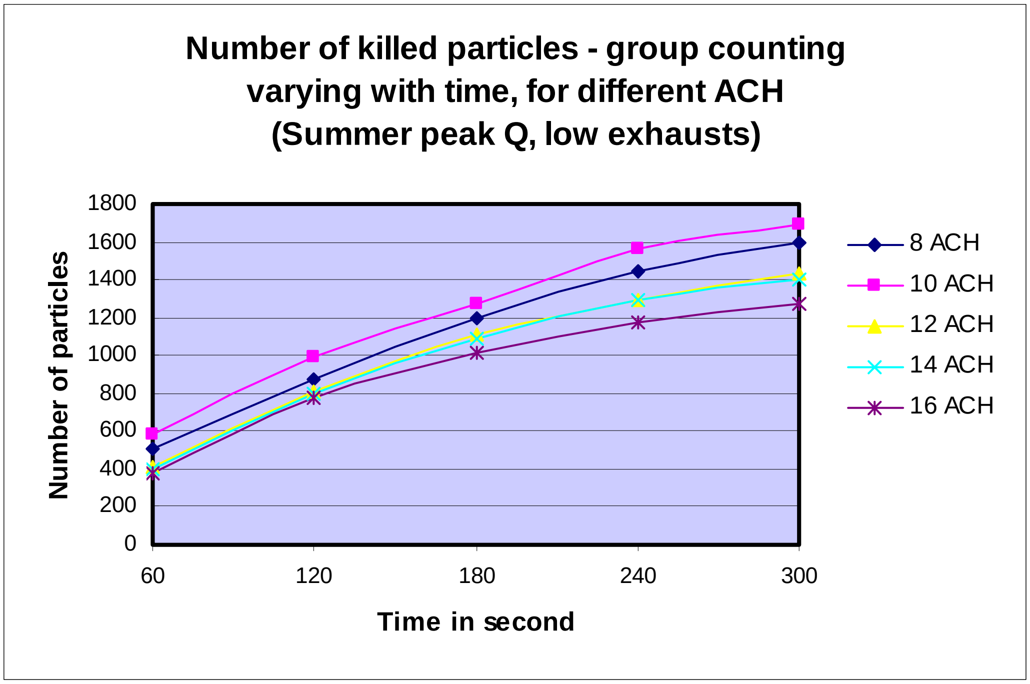

Figure 5.30. *Number of killed particles with ACH change (Summer peak Q)*

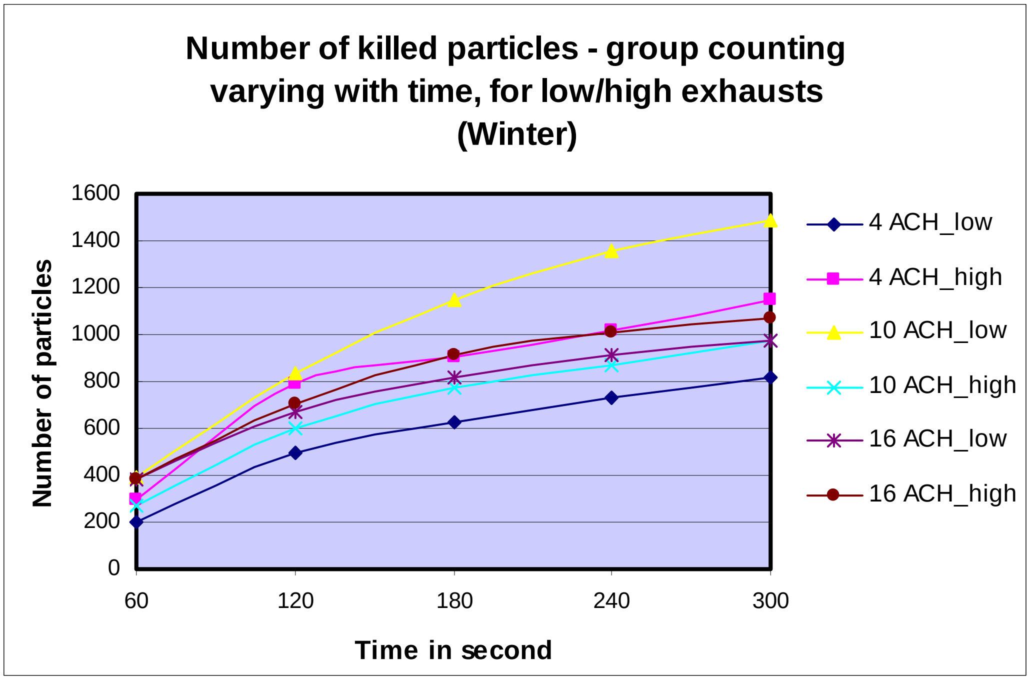

Figure 5.31. *Number of killed particles with exhaust location change (Winter)*

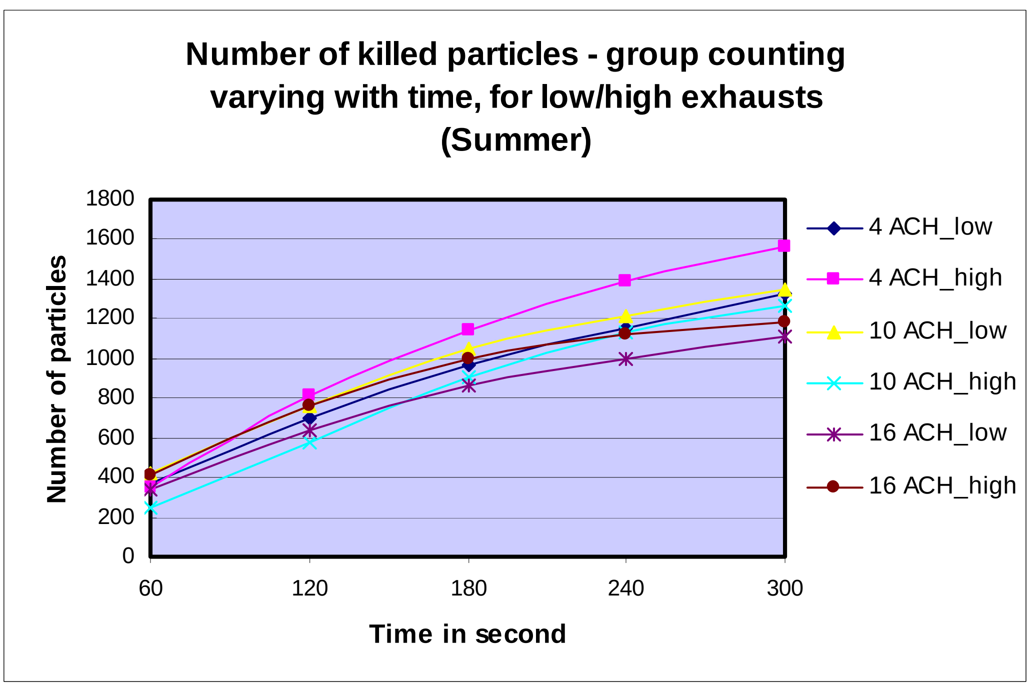

Figure 5.32. *Number of killed particles with exhaust location change (Summer)*

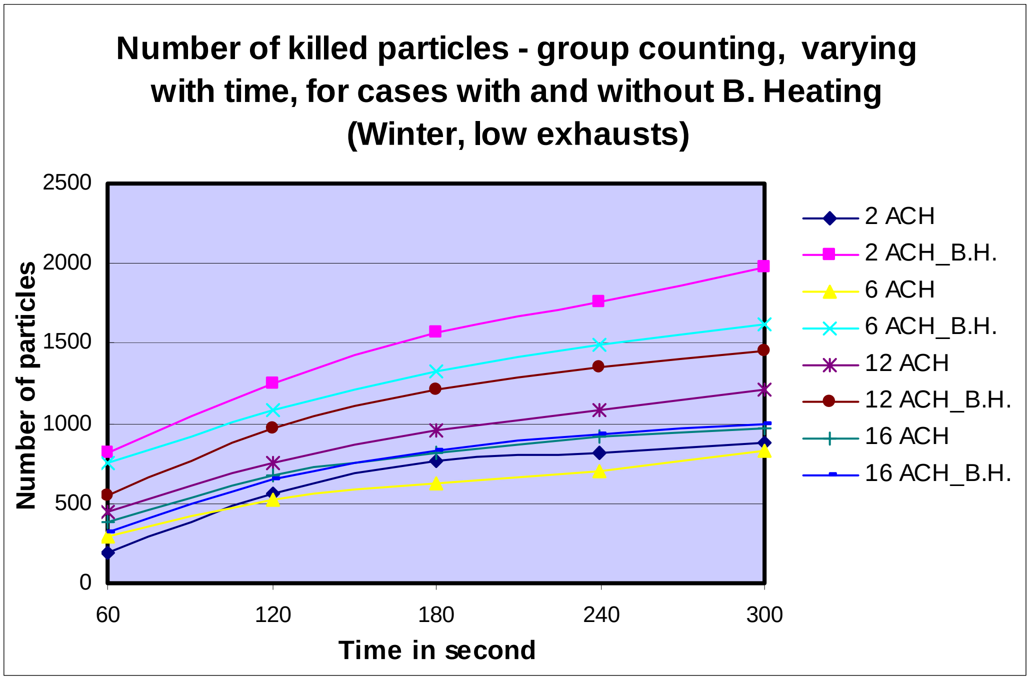

Figure 5.33. *Number of killed particles for cases with/without Baseboard Heating*

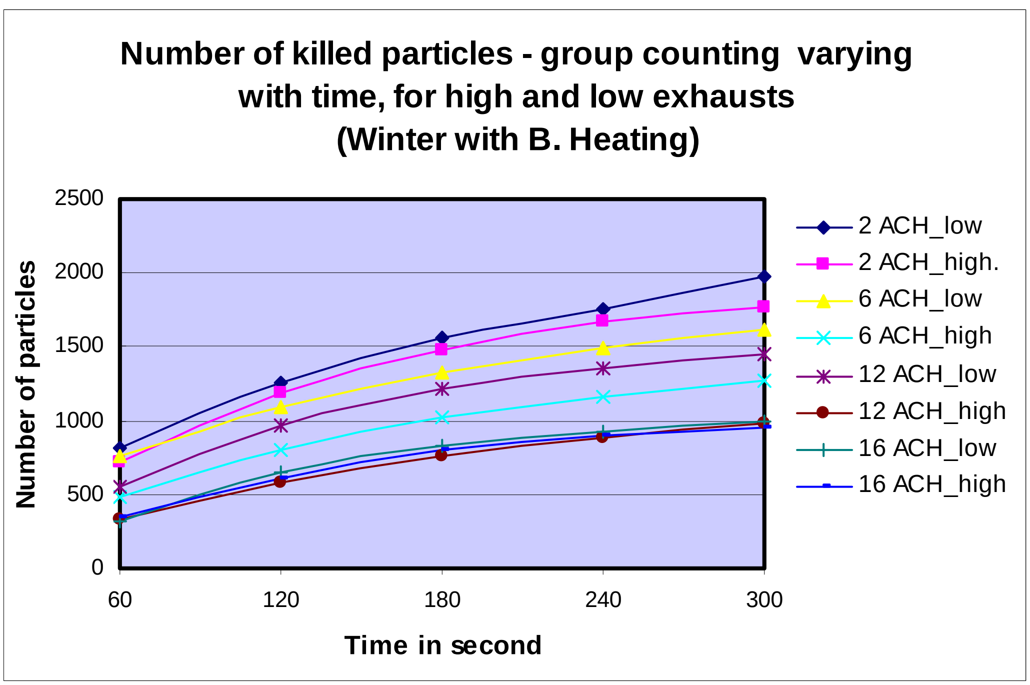

Figure 5.34. *Number of killed particles for exhaust location change when baseboard heating is applied*

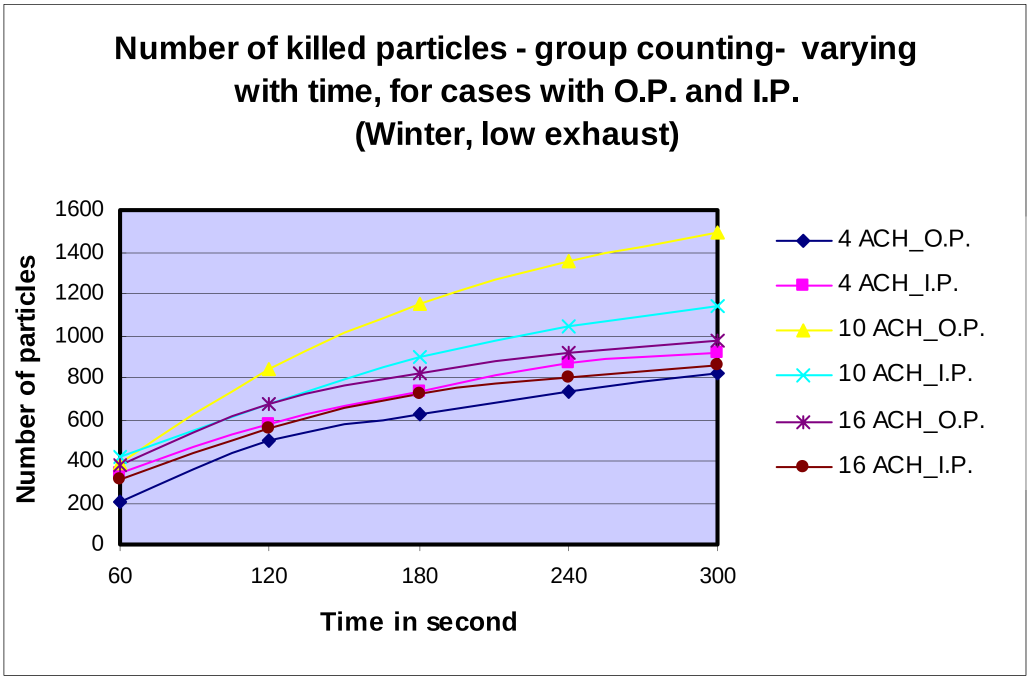

Figure 5.35. *Number of killed particles for cases with original/ increased pressurization (Winter)*

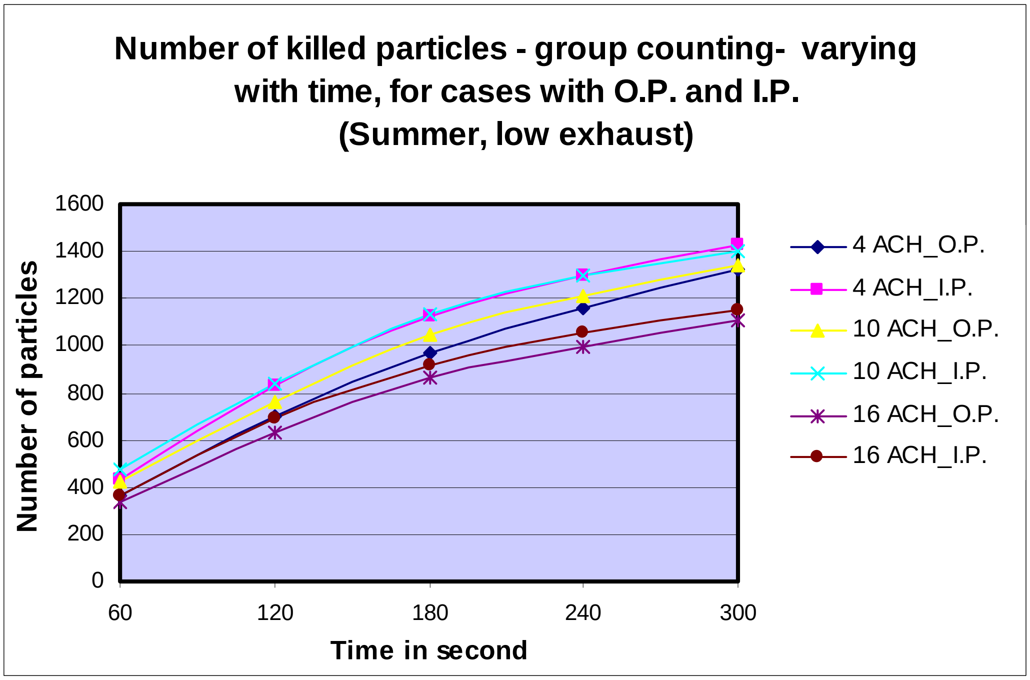

Figure 5.36. *Number of killed particles for cases with original/ increased pressurization (Summer)*

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.

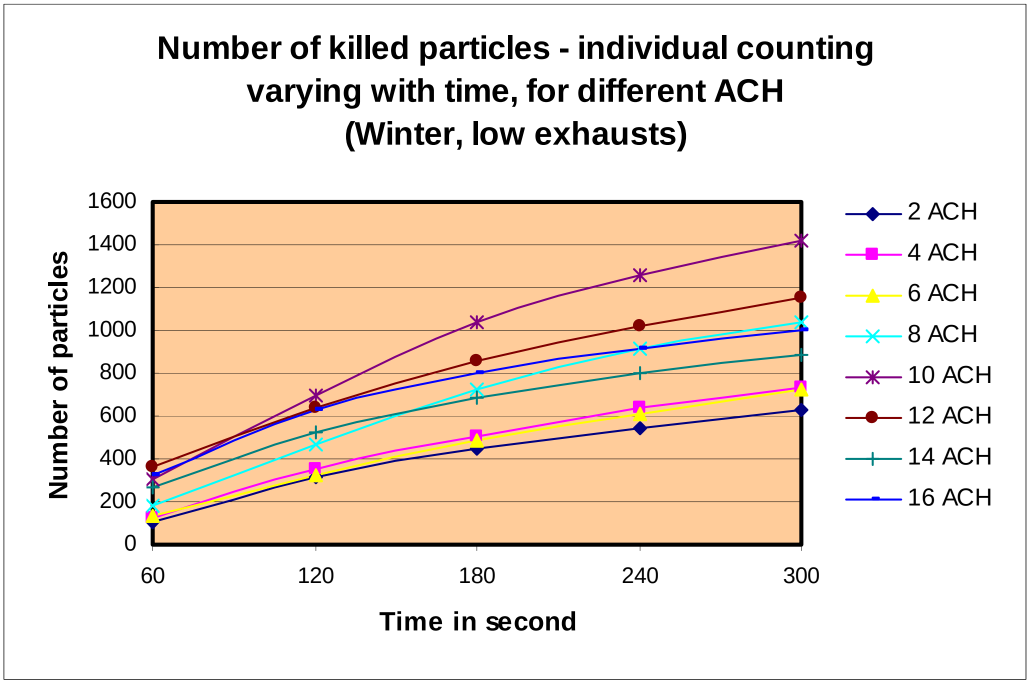

Figure 5.37. *Number of killed particles - individual counting - with ACH change (Winter)*

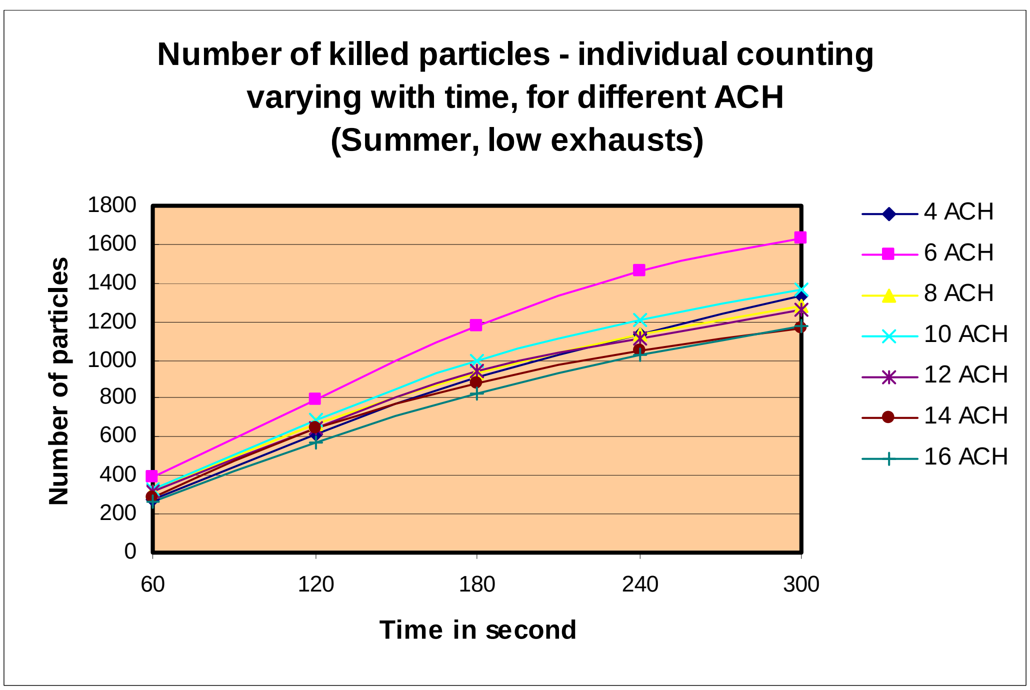

Figure 5.38. *Number of killed particles - individual counting - with ACH change (Summer)*

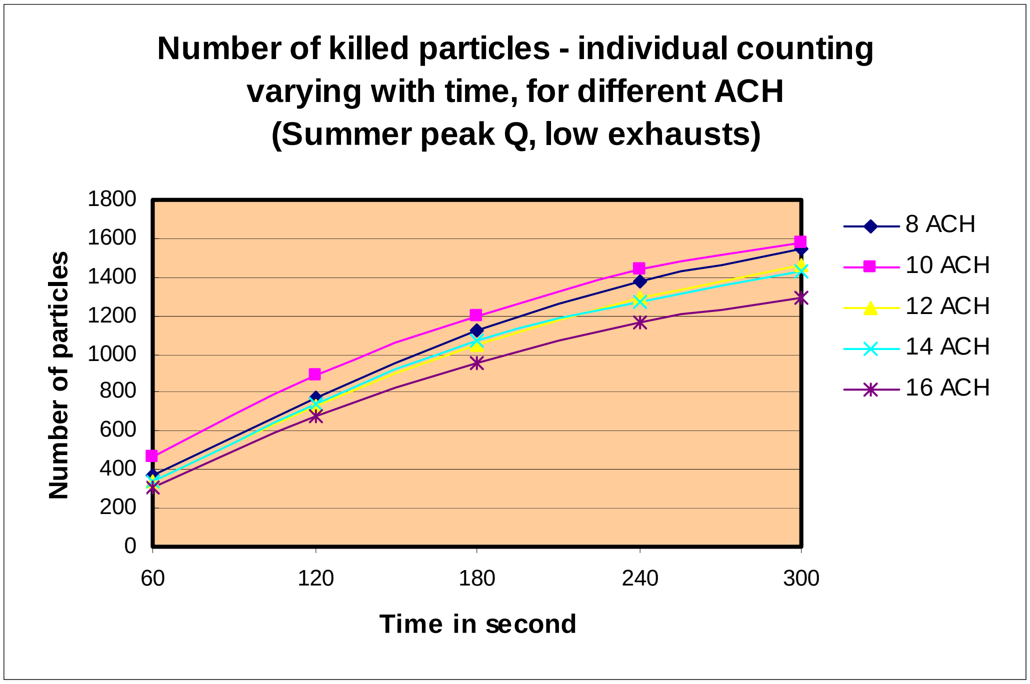

Figure 5.39. *Number of killed particles - individual counting - with ACH change (Summer peak Q)*

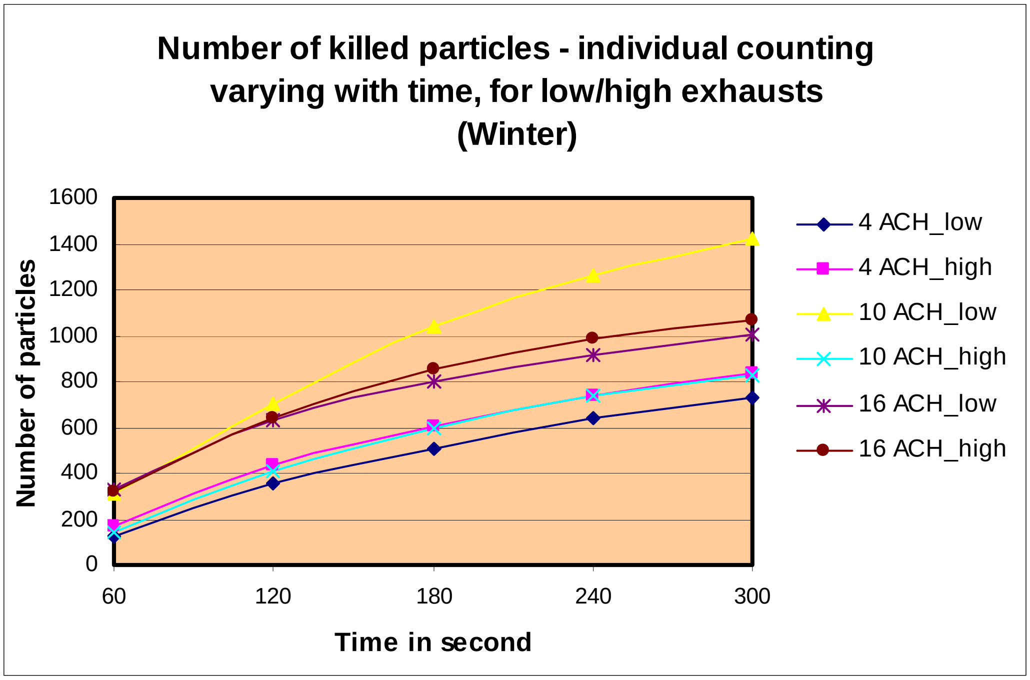

Figure 5.40. *Number of killed particles - individual counting - with exhaust location change (Winter)*

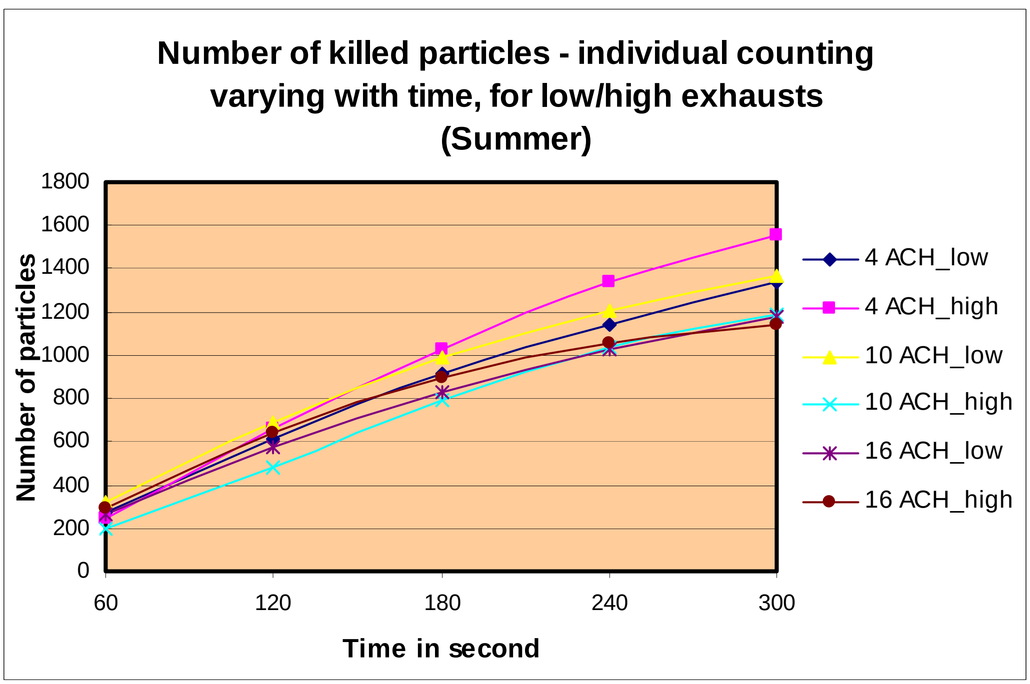

Figure 5.41. *Number of killed particles - individual counting - with exhaust location change (Summer)*

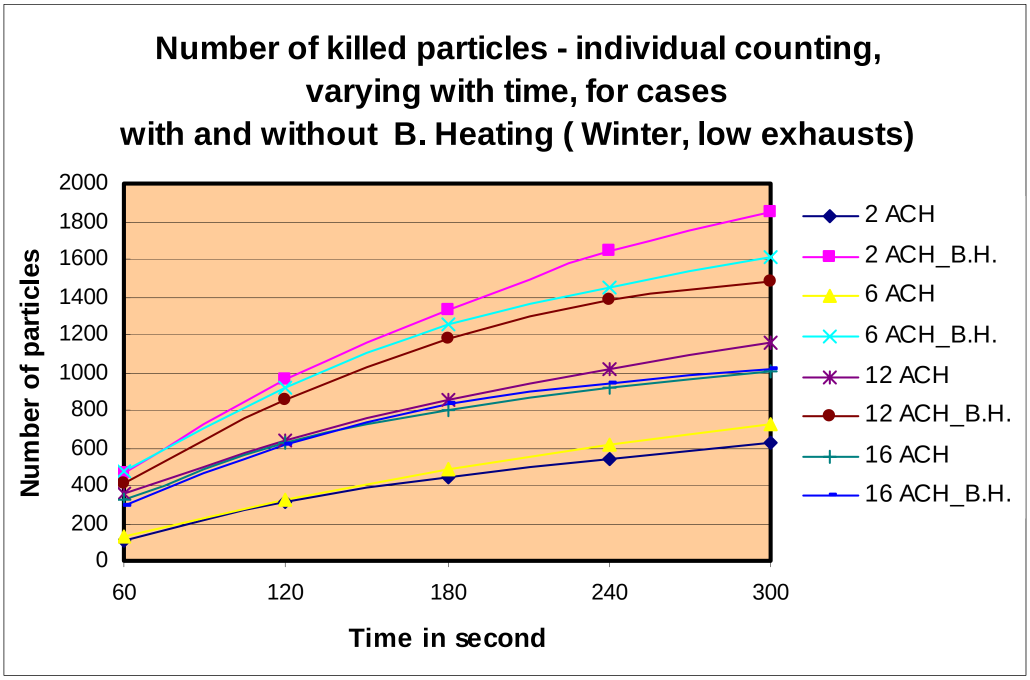

Figure 5.42. *Number of killed particles - individual counting- for cases with/without Baseboard Heating*

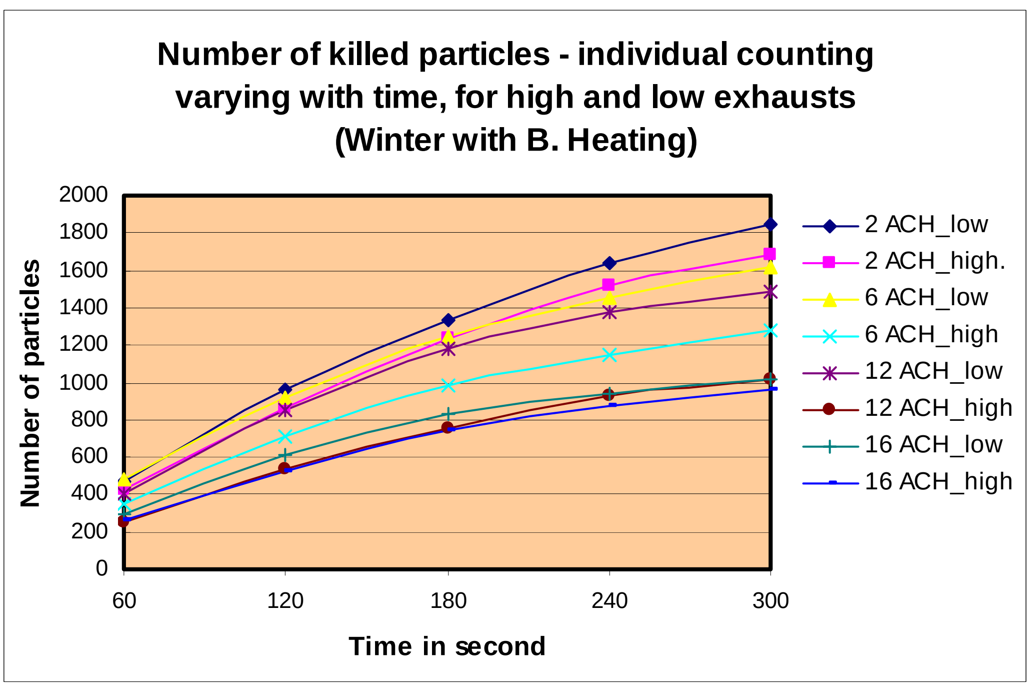

Figure 5.43. *Number of killed particles - individual counting - for exhaust location change when baseboard heating is applied*

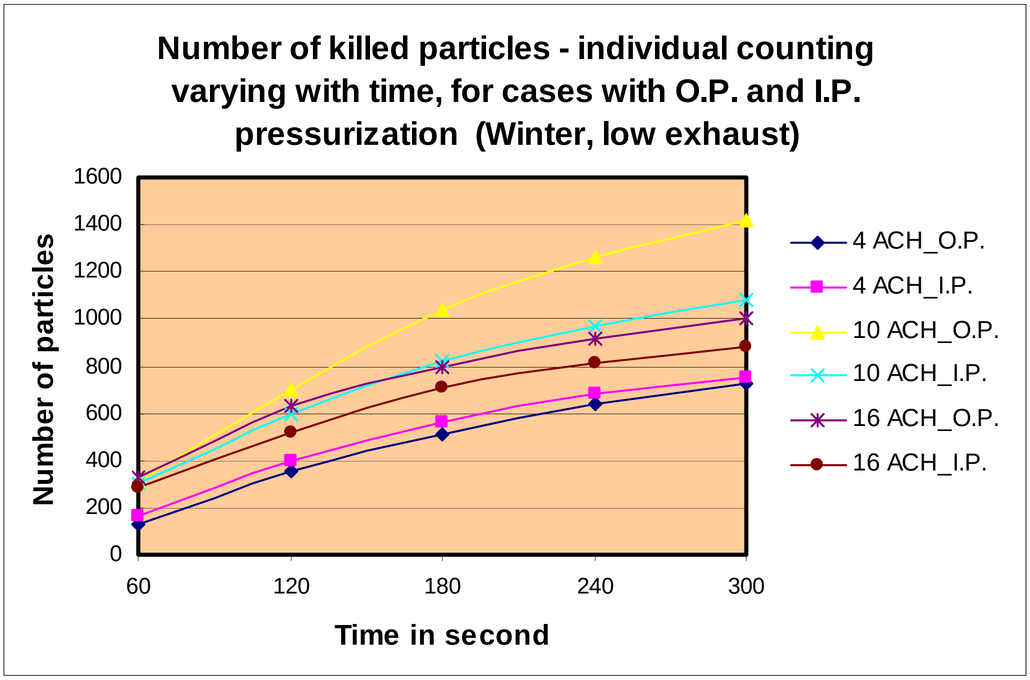

Figure 5.44. *Number of killed particles - individual counting - for cases with original / increased pressurization (Winter)*

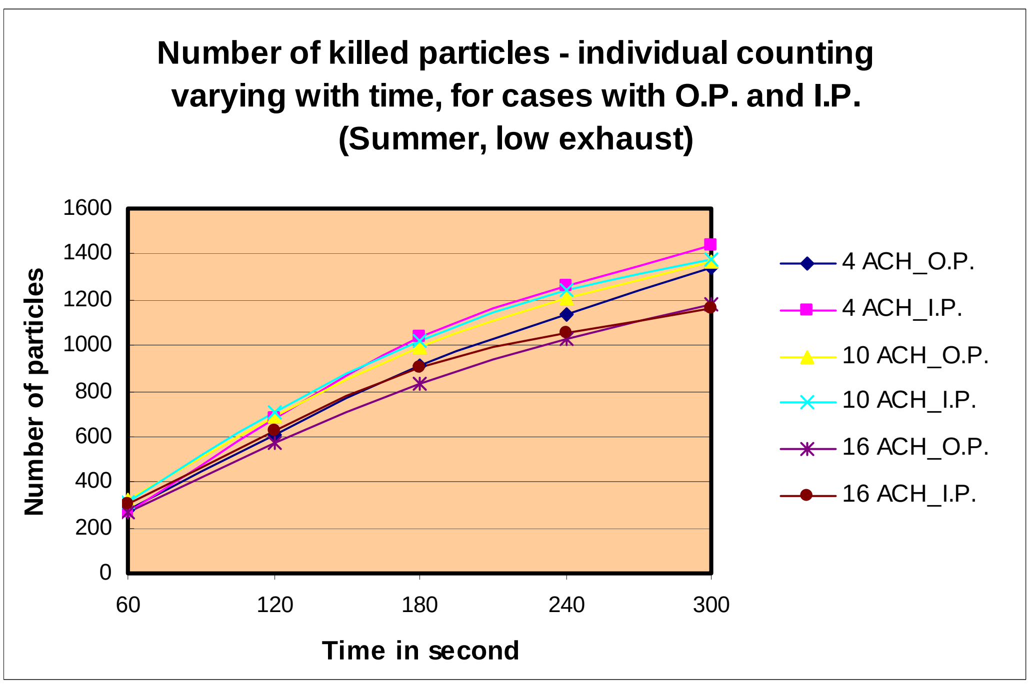

Figure 5.45. *Number of killed particles - individual counting - for cases with original / increased pressurization (Summer)*

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.

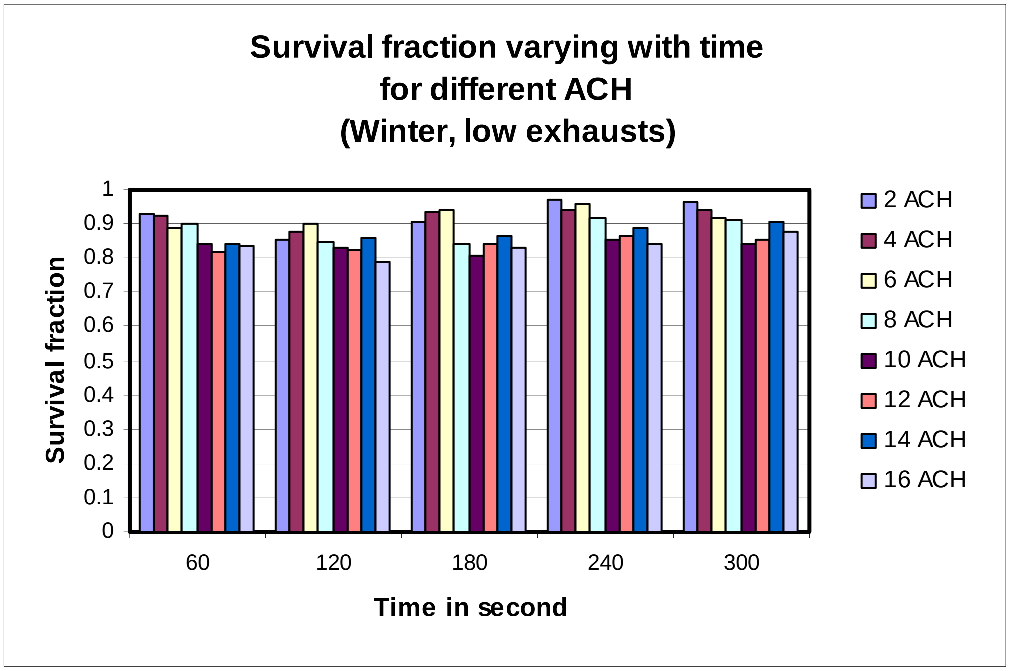

Figure 5.46. *Survival fraction with ACH change (Winter)*

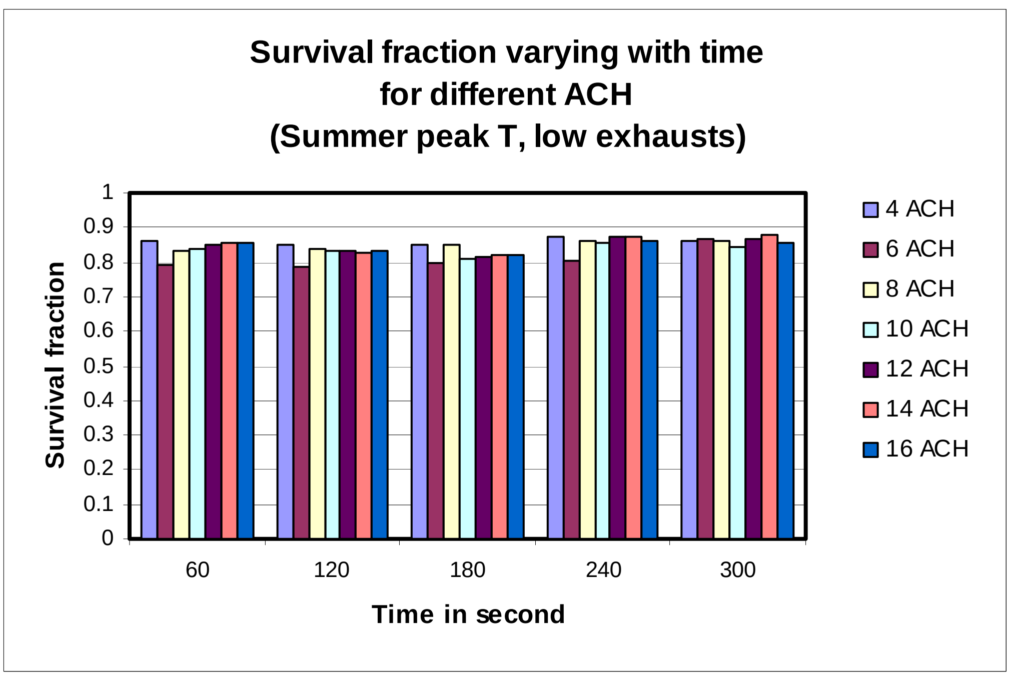

Figure 5.47. *Survival fraction with ACH change (Summer)*

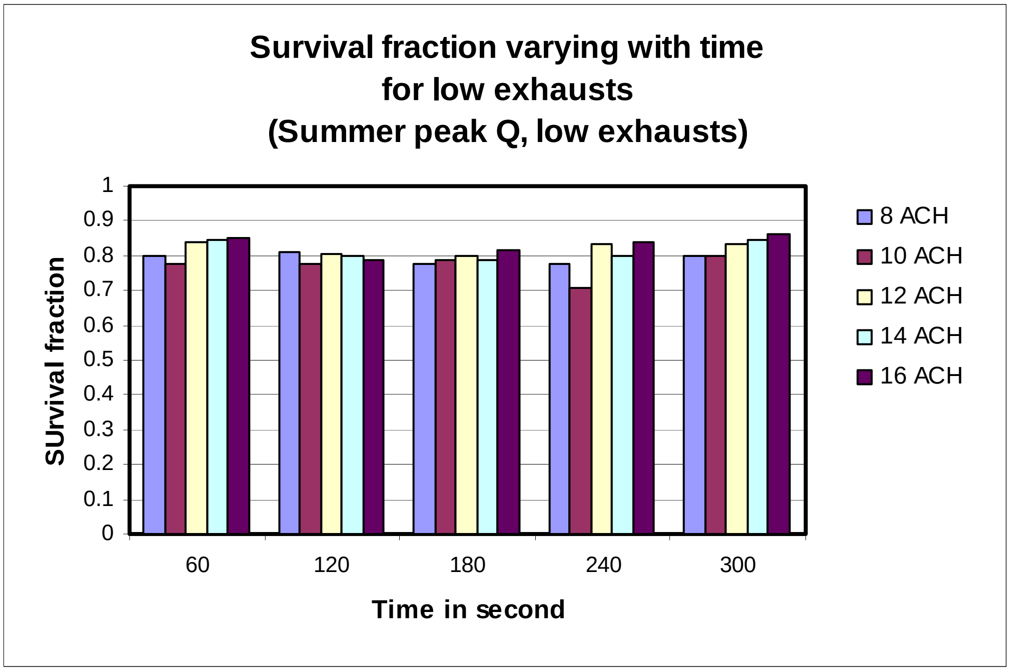

Figure 5.48. *Survival fraction with ACH change (Summer)*

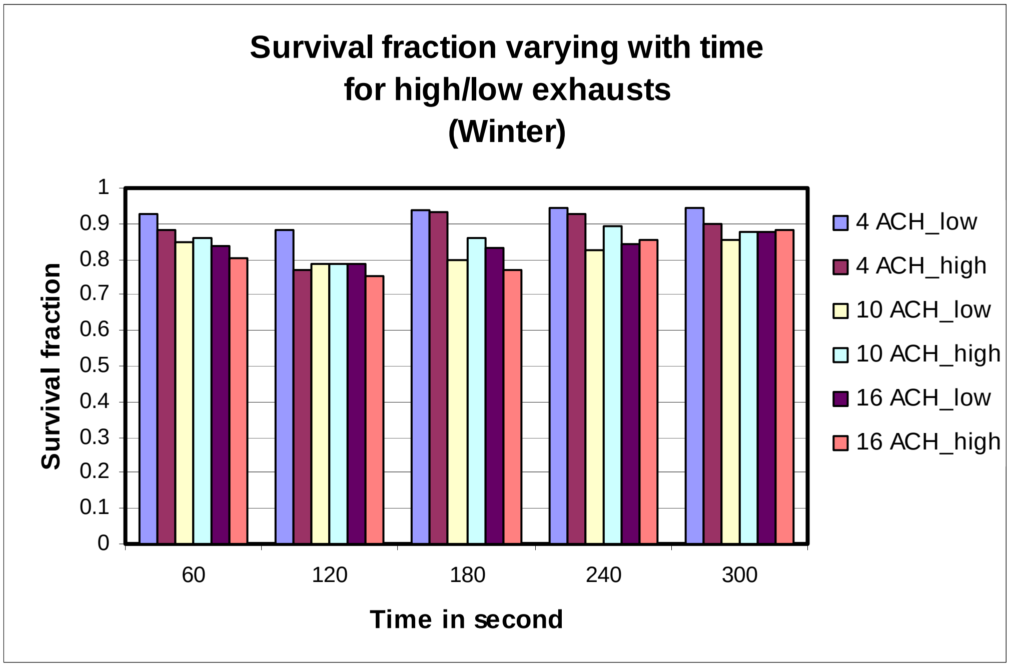

Figure 5.49. *Survival fraction with exhaust location change (Winter)*

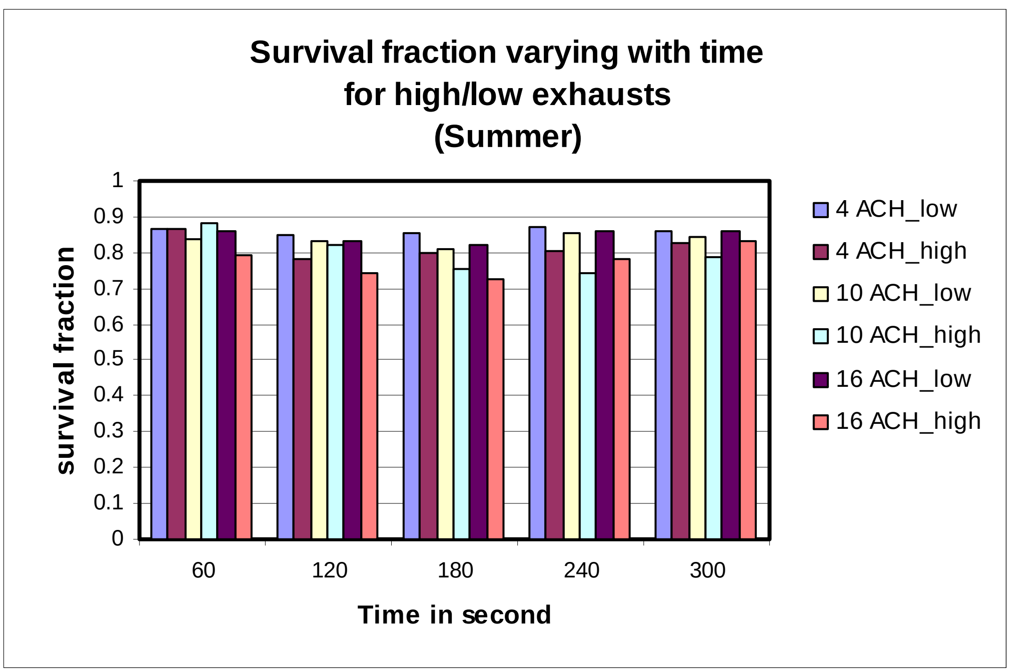

Figure 5.50. *Survival fraction with exhaust location change (Summer)*

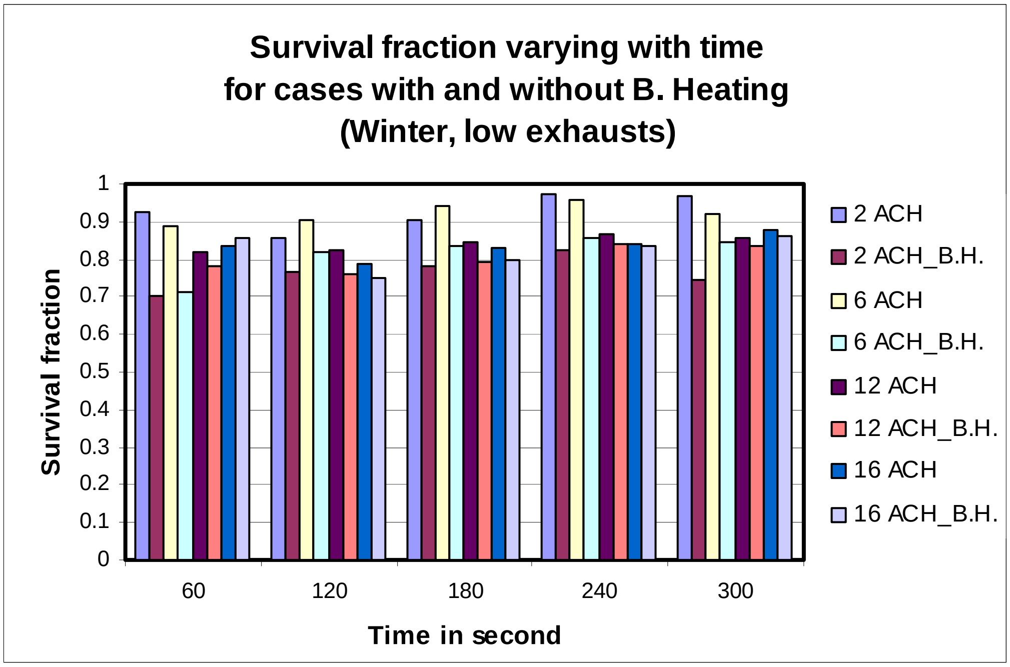

Figure 5.51. *Survival fraction for cases with/without Baseboard Heating*

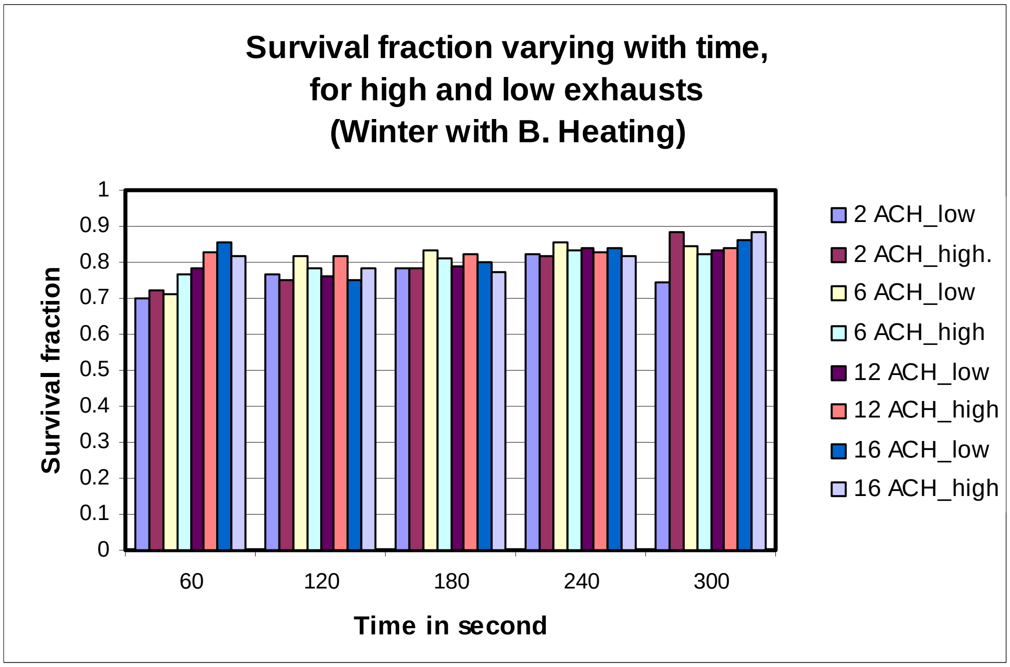

Figure 5.52. *Survival fraction for exhaust location change when baseboard heating is applied*

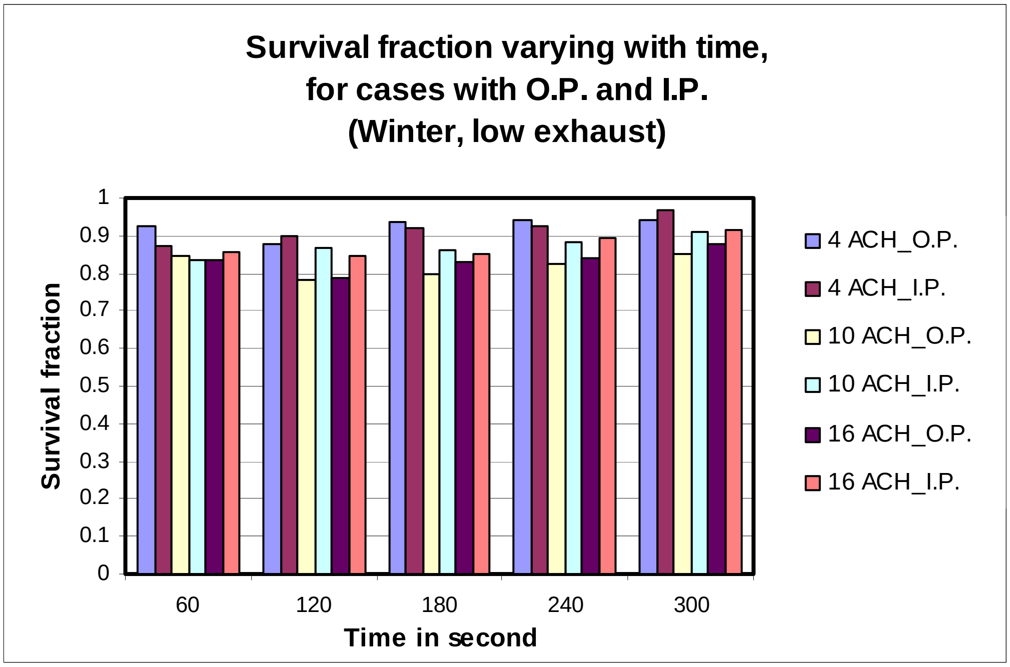

Figure 5.53. *Survival fraction for cases with original/ increased pressurization (Winter)*

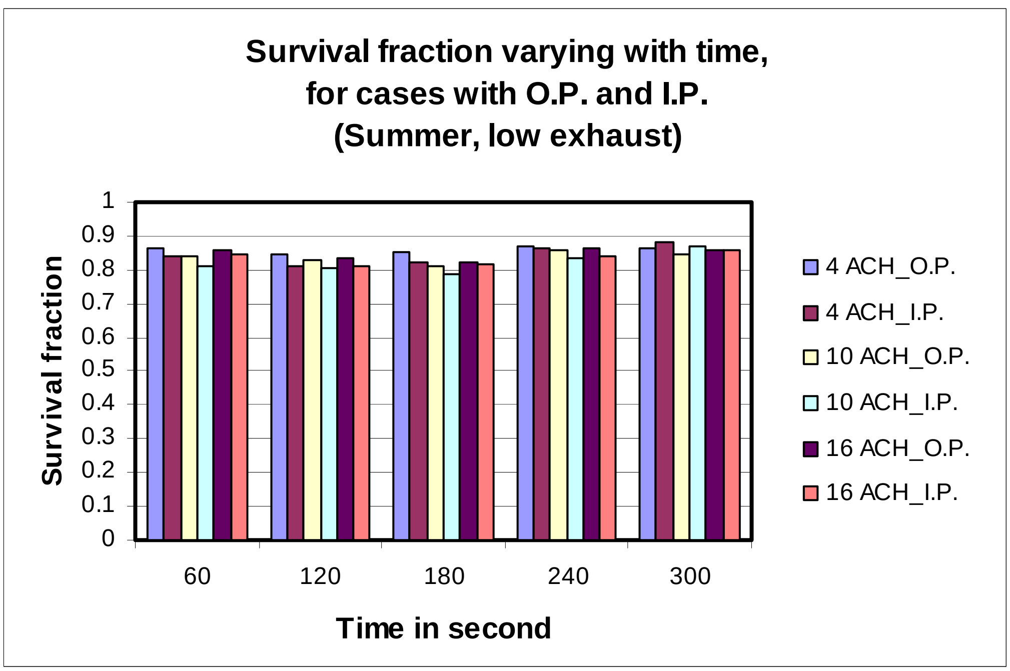

Figure5.54. *Survival fraction for cases with original/ increased pressurization (Summer)*