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Effects of Architectural Somatic Variables on Mixed Air Conditioning Systems' Efficiency in Industrial Buildings

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ABSTRACT: Providing welfare status for personnel of industrial plants is necessary and also emphasized in all standards. Preparing fresh, cool and clean air especially in warm seasons is one of the most important duties of plant owners to keep workers safe and healthy. Although in many workshops some cooling and air-conditioning systems (commonly mixing ventilation systems) were installed, most of them have economical problems and may not be energy efficient as the entire room volume gets cooled. The purpose of this article is presenting an executive improved solution in architecture to upgrade existing Mixing Ventilation Systems (MVS) by intervening in architectural variables. The new solution is compared with a traditional MVS taking into account technical and economic performances. The study was carried out resorting to experimental measurements on a single-diffuser pilot installation of the existing MVS in an actual industrial facility. The research method is experimental: the thermometry tests and interviews with workers which were carried out after initial observations and the case study selection. After that some interventions in architecture were impelled and the testes were repeated. To confirm the results, after interventions, a questionnaire was given to the operators, and their answers were registered. A comparison was fulfilled with respect to energy consumption and also the consumed power was checked before and after the interventions. The results demonstrate that architectural alterations based on this research can improve the quality of existing MVS (Satisfactions of the workers approved the interventions) and reduce the energy consumptions. It could be generalized.

Keywords: Intervening in Architecture, Industrial Buildings, Air Conditioning, Indoor Airflow, Mixing Ventilation Systems (MVS).

INTRODUCTION

During summer months a ventilation system is required in most industrial facilities to maintain comfortable conditions in the workplace. Usually this is carried out resorting to a mixing ventilation system (MVS). Mixing ventilation involves cold air injection from the upper part of the room, and exhaust of warm air from grilles located at ceiling or floor level according to the specific building requirements (Fig. 1). Turbulent mixing of the cold stream with ambient air determines the uniform cooling of the whole volume. The energy expenditure can thus be relevant, especially when high-ceiling buildings are considered or when high thermal loads exist in the shop floor, because a fairly constant temperature level is achieved in the entire room volume, with negligible vertical temperature gradient, and even the upper part of the room, not occupied by people, gets unnecessarily cooled (Caputo, A. C., & Pelagagge, P. M., 2008).

An alternative ventilation method is a displacement ventilation system (DVS) which includes injection of cold air in the lower part of the room, in proximity of the floor, through proper diffusers, while the heat sources in the room cause upward moving convection flows transporting warmer and polluted air from the lower part of the room to the upper part from where it is exhausted. The resulting air stratification effect enables a better indoor air quality in the lower level and the effective cooling of only the lower volume of the room, where people operate. As a result, respect a MVS the same microclimatic conditions

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may be obtained in the volume occupied by workers but with lower energy expenditure (Khorasanizade, H. et al., 2010).

However, the steeper vertical temperature gradient is usually the limiting factor for DVS, because the temperature difference between feet and head of workers should be limited to around 2^{oC} (and maintained lower than 3^{oC}) to avoid discomfort (Caputo, A. C., & Pelagagge, P. M., 2008). In practice, this imposes a constraint to the performances of DVS as when the cooling load is high, the amount of air needed to keep the temperature gradient below this limit will be too large and cause problems with air handling and distribution.

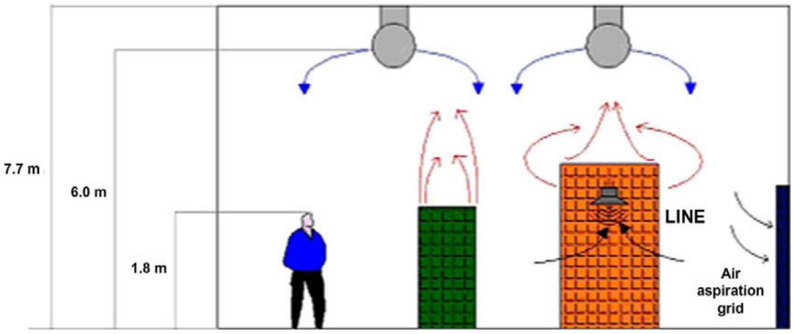


Fig. 1. Scheme of Mixing Ventilation System (MVS)

THE PROBLEM

In MVS, injecting cool air from the upper parts of the inner spaces causes turbulent mixing of the cold stream with ambient air. So the uniform cooling of the whole volume occurs. It seems that although this method is popular in industrial workshops, it's not effective enough to cool all inner air of the factory mostly because of the architectural problems. According to the research, the time consuming cooling process can't keep comfort state of all operators, however energy consumption in such systems is high and subsequently the cost of that is high too. The inefficiency of the system can thus be unleashed especially when high-ceiling buildings are considered or when high thermal loads exist in the shop floor. It's too serious when the main doors of the plant must be opened many times through a day work. Other architectural variables make the inefficiency critical. In many workshops, because of the mentioned problems (cost, energy consumption and inefficiency of the cooling) the MVS is off (though they are installed) through the work time in warm days. In some newly built cases, according to the researches, the air conditioning systems are completely erased (because of inefficiency) and, the owners prefer to use opened big doors, jet fans and water coolers instead of them to make a weak stream of air in inner spaces. According to the research the workers of such plants have a risky and uncomforted state especially in warm days, while the cooling processes is just needed in lower parts of the inner spaces where the workers are working. Because of the standards, humidity and hygienic reasons the usage of water cooling systems are not advised also and is not the matter of this article.

METHODOLOGY

The purpose of this article is to propose a solution to improve the existing MVS's quality in workshops by making alterations in architectural variables and develop an optimized- economical system by intervening in architectural parts of the factories. Since the study involves several fields and "many architectural researches are interdisciplinary and require special combined techniques" (Groat, L. & Vang, D., 2004) so this study is interdisciplinary. An experimental assay in a real case study was occurred. The statistical population in this study includes all workshops, labs and plants which have at least a large industrial chamber with a high elevated ceilings and the cooling processes is highly necessary in warm days. So the research method in this study is as following:

After studying the popular existing air conditioning systems in the statistical population a case study was selected to fulfill experimental periodic testes; the random case must have MVS and must be around Tehran with easy access. So a hygienic production's plant in Kaveh

Industrial Area was considered as case study. With an experimental strategy the periodic testes of thermometry were done in case study. The testes were carried out around some single-diffuser pilot installations of the existing MVS. Then after intervening in architectural part of the building specially ceiling and altering in indoor airflow, the testes were repeated. To confirm the results a questionary was given to the operators and workers, and the answers were registered. A comparison was fulfilled between the consumption of energy, before and after the interventions also. Finally after analyzing the data, generalization of the results was carried out and some proposals for new industrial facilities were presented.

LITERATURE REVIEW

A research shows that from 1940s a great concern about industrial ventilation has been occurred in the world (Burgess, W. A., 1995). Many of the information gathered by the researchers were published in initial editions of Source Book of Industrial Ventilation (ACGIH, 1951). From 1920s New York Federal Organization of Industrial Standards, HSE Department published periodical journal of Review about ventilation and workers safety. From 1950s journal of Michigan's Occupational Health about air conditioning, ventilations and worker's health was initiated. Soule (1991) considered both local and general exhaust ventilation systems for plants and proved that both systems are necessary for each plant (Soule, R. D., 1991, pp. 24-93). Environmental Agent Factory Establishment Standards (2001-6) and Euro Standards (2006) were established to emphasize saving energy, reducing environmental pollutions, cooling and ventilation in plants (Curd, E., 2006). COSHH[1] from HSE of Britain, REL[2] from America, NIOSH[3], PEL[4] and OSHA[5] are international standards that emphasize on ventilation's necessity in plant and Iran's Technical Committee of Professional Hygienic has confirmed them.

Prediction of indoor airflow in buildings and the rate of heat and pollution transmissions can give useful information to designers for optimizing designs. Indoor airflow's information in closed spaces is notable for 3 reasons: thermal comfort, indoor air quality and energy consumption. The studies show that "indoor airflow" as a distinct new science especially in last 2 decades was appeared (Amidpoor, M., 2010). There are 2 methods for airflow analysis: experimental methods and digital simulations. Since experimental methods needs under-controlled real buildings and are expensive. The device's errors that are not ignorable depending on the device's accuracy and the circumstances (Loomans, M. & mook, F. van, 1995). The digital simulations in comparison with the experimental methods are easier, more accurate, and under control, but they need some proximate assumptions (Amidpoor, M., 2010). Park and Holland used digital analysis in their DVS researches and the accuracy of the method was approved with experimental tests. They demonstrate that in DVS, vertical temperature gradient is not under control (as a serious problem) (Park, H.J. & Holland, D., 2001, pp. 883–889). Furthermore DVS was considered and analyzed by Novoselac (Novoselac, A. & Srebric, J., 2002, pp. 497–509), Rees (2001) and Ghali (Ghali, K. et al., 2007, pp. 743–759) in combination with cold roofs. Rees showed that in DVS, temperature of the roof has not an important role in confusing the thermal welfare of the workers. The vertical temperature gradient is not predictable also (Rees, S.J. & Haves, P., 2001, pp. 753–762). Arenz (2000) used and presented experimental thermometers, density, and wind speed in a real plant's workshop and office to explain the suitability it's MVS and assay the DVS of a chamber with 6.5m hight. He showed that the DVS is more efficient, but the vertical temperature gradient is not predictable, however in comparison with MVS the energy consumptions is less (Arenz, A. D., 2000).

GENERAL OBSERVATIONS

The main benefit of DVS in respect of MVS is owing to the temperature stratification effect, only a fraction of total heat loads considered in the MVS that are to be satisfied. This enables substantial energy savings. This advantage becomes even more relevant in high-ceiling buildings where, otherwise, the entire room volume would be cooled uniformly by the MVS even in the upper room portion where people are not present. However, very little performance data exists for displacement ventilation in high-ceiling rooms (from 5 to 20 m) which are characteristic of many industrial facilities. However, in practice, the conversion from a MVS to a DVS in a building is constrained by the existing mixing ventilation ductworks, which often cannot be dismissed owing to economic reasons. In DVS the vertical temperature gradient is not predictable also. So a more viable alternative can therefore be a retrofitted existing MVS into a new hybrid system that resemble DVS without its problems by intervening in architectural details of the building. This new hybrid system must have the privileges of both systems and accord to the architecture. So some plants (18 factory) belonging to statistical population of this research were considered. Because of the private sector's problems, registering the observations and the problems of ventilation was enabled just in some few cases:

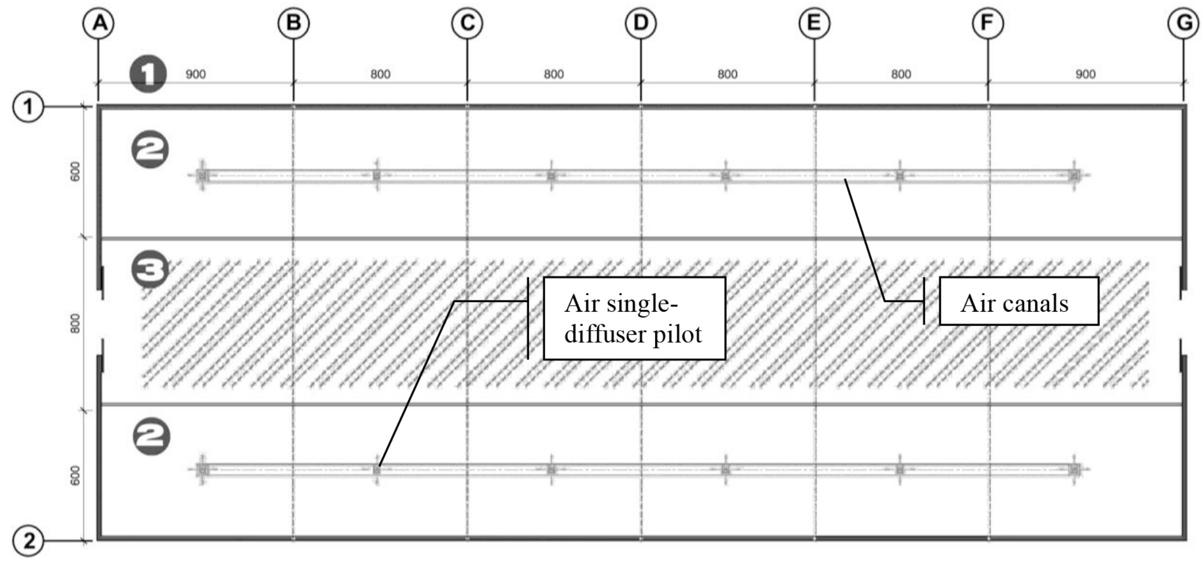
Iran's Electrical Tools factory has 2 large saloons with 10m height and 20m span. There is a bank of windows (2 meter height) in both side walls right beneath the roof. Smoke testes showed that there is no indoor airflow in each condition (Fig. 2). The plan of Pars Cast Iron' is like Iran's Electrical Tools factory with 12m height. However the indoor air pollution is critical, just incomplete natural ventilation could be carried out through the overall opening in the middle of the roof and the gates. Tehran refinery's central workshop has the same problem and all MVS and industrial general ventilation's devises was usually off because of the inefficiency. In Tehran refinery's lab (ceiling's height: 4m) the cooling process was carried out by MVS through ceiling's diffusers. But thermal comfort of the operators was a great problem when even a little window was open (Fig. 3). The interviews with the workers and operators of visited plants approved the problem.

Fig. 2. East- West Extension of Industrial Buildings in Chardongeh

Fig. 3. Central Workshop of Tehran Refinery. Dead Spaces with No Use are Highlighted. All MVS is Off and the Gates are Open Instead.

CASE STUDY

The case study of this research is a hygienic production's plant in Kave industrial area. It has a rectangular saloon (20 m x 50 m) with a standard MVS for air conditioning. It's an east west building with 2 big steel gates (3.5 m x 3.5 m at the middle of the east and west walls). So when the gates are open, a permanent current of wind will blow inside the plant. Peripheral brick walls are thick (35 cm) and the roof is a kind of sandwich panel with double skin. The floor is plane and Work places were separated just by light partitions and the air diffusers installed in the ceiling, 3 meters far from side walls (Fig. 4). Following Fig. 4, there are 12 single diffuser pilots in 2 parallel lines both sides of the main axe of the plant that passes through the gates.



1. Outdoor 2. Workplace 3. Passage way (there is no devices)

Fig. 4. Ground Floor Plan of Hygienic Production's Plant in Kave Industrial Area (Case Study).

Different devices with different thermal load in the shop floor are problems for existing MVS. High thermal loads especially when the gates are open can make the comfort state critical. This state is inevitable and the gates at least must be open several times a day. A questionary provided and the viewpoints of the workers about the existing MVS were registered. Just 10% of interviewees were not satisfied of cooling system (comfort state) when all opening are closed and the MVS is on. The unsatisfied people worked around the devices with high thermal loads. But when just a few openings are appeared, there are more unsatisfied people because of the inefficiency of existing MVS. Following the diagrams in Fig. 5-8, when all openings were closed and the MVS is on (in warm days) comparably there is a kind of satisfactory. But when the openings are open, there is not much difference if the MVS is on or off (Fig. 5-8)

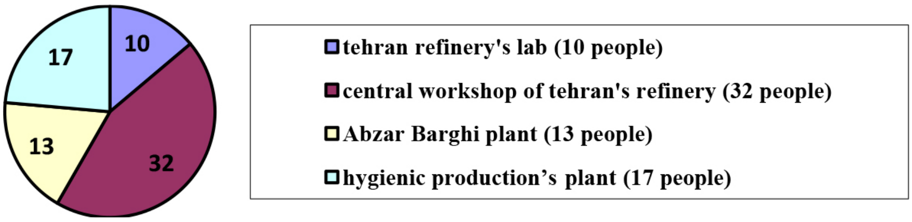


Fig. 5. Comparing Chart of Number of Interviewees in Different Workshops

So the existing MVS can be partly effective just if all openings are closed and no devices has thermal load. In this manner, more thermal load can change the comfort condition. Cooling all indoor air can consume more than enough energy, because cooling the workers level is just necessary and there is no need to cool the air above the workers. So in many cases, the MVS is usually off because of the inefficiency. The study shows that some intervening in architecture can make the existing MVS optimum.

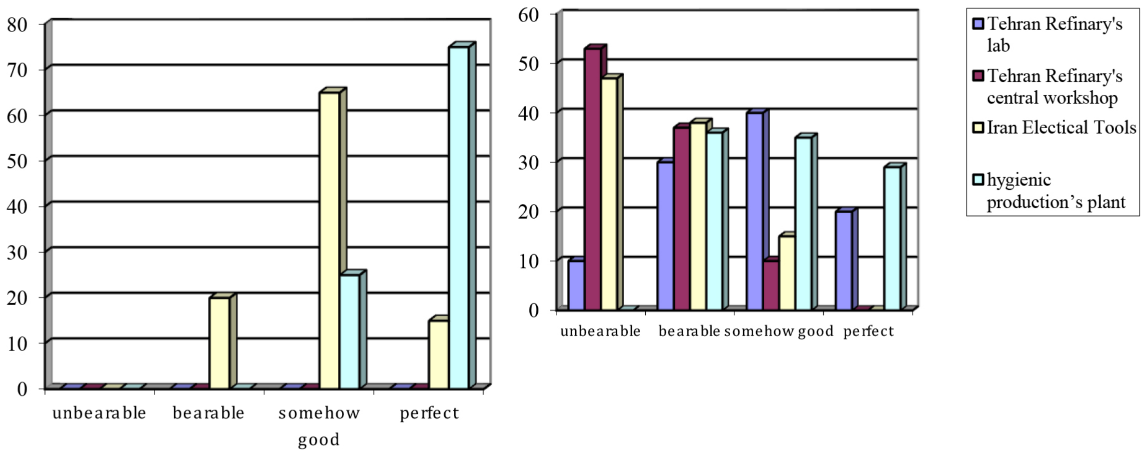


Fig. 6. Interviewees' Issues about the Rate of Satisfaction of the Existing MVS When it is on and All Openings are Closed. Up: Before Intervening, Left: after Intervening

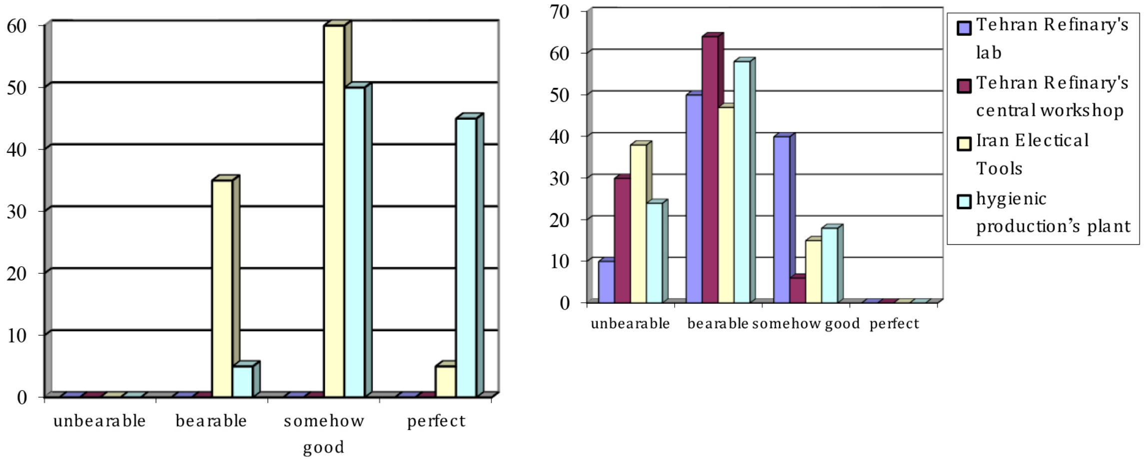


Fig. 7. Interviewees' Issues about the Rate of Satisfaction of the Existing MVS when it is on and Some Openings are Open. Up: Before Intervening, Left: After Intervening

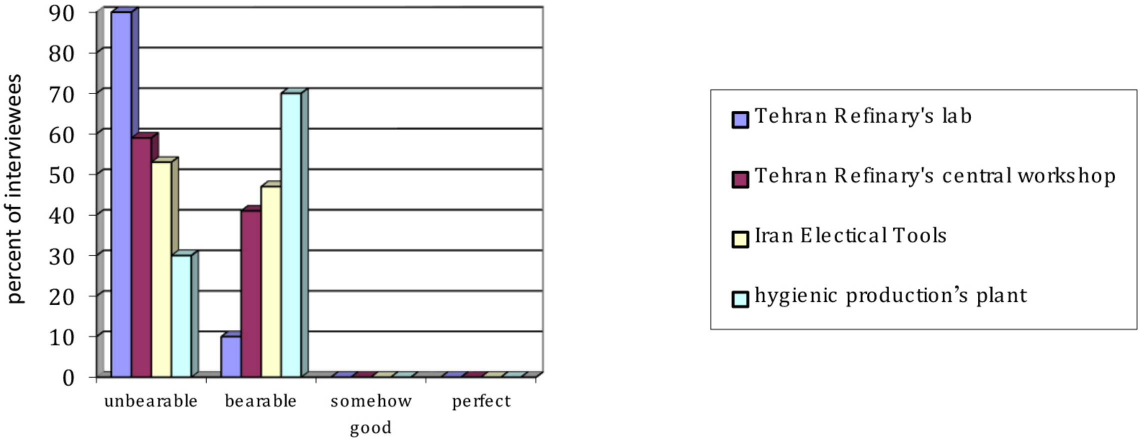


Fig. 8. Interviewees' Issues about the Rate of Satisfaction of the Existing MVS when it is Off and the Openings are Open

EXPERIMENTAL TESTS AND INTERVENING IN ARCHITECTURE

This study assumed that intervening in architecture can improve existing MVS and optimize indoor airflow. To prove the theory, in the case of this study some experimental tests, before and after intervening in architecture, were assayed and the results were registered. A vertical partition was hanged from the ceiling (indoor the plant) above the operators. It was 3.5 meters away from the sidewall. The hanged partition (height: 2 meters) was set as showed in Fig. 9 and covered just an air single-diffuser pilot (Fig. 9, 10). On a vertical rod near the test-diffuser, three levels of +3.5 m (point A), +1.5 m (point B), and +0.5 m (point C) were marked above the floor (point D). The thermometry tests were done at marked points (A, B, and C) before and after intervening (Fig. 12) in both conditions of existing MVS: on and off. The aim of this intervening is the performance improvement. It was assessed referring mainly to the obtained vertical temperature gradient: in the lower part of the room (up to a height of 2 m) a suitable temperature must be gotten (in the workers' level) and higher temperatures in the upper parts of the room (no matter how much it is) in order to save more energy.

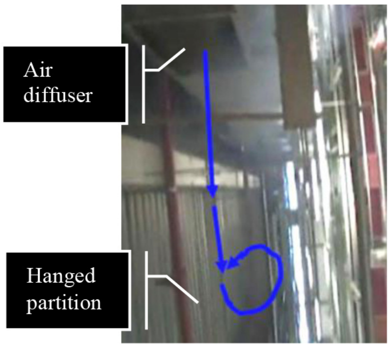


Fig. 9. The Single Diffuser Pilot for Experimental Tests of the Study

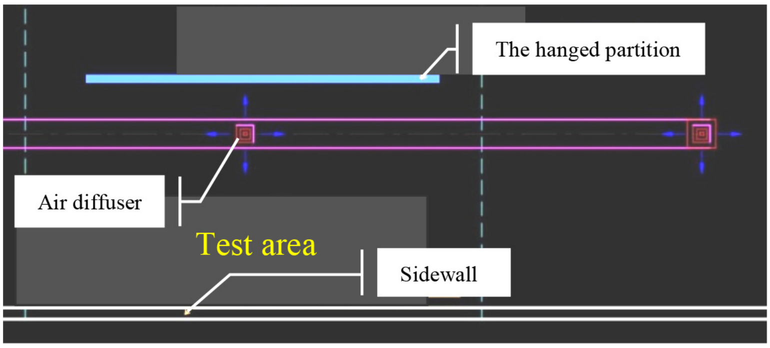


Fig. 10. Position of the Hanged Partition in the Case Study. The Air Diffuser is between Sidewall and the Hanged Partition.

Fig. 11. The Facade of the Hygienic Production's Plant, Kave Industrial Area (Case Study)

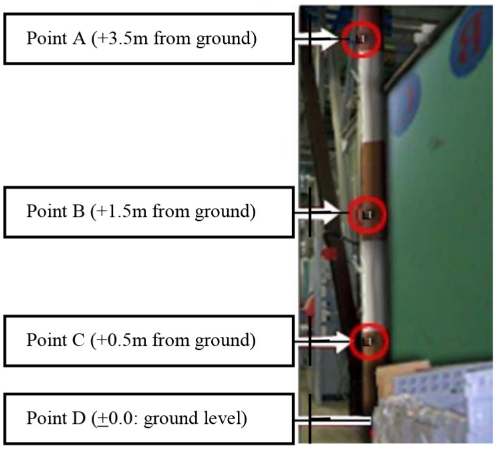


Fig. 12. Test's Point in Test Area of Case Study

Table 1. Thermometry Assays in 2011 and Registry of the Average Daily Temperature of the Test's Points in Test's Days. All Units are in ^{oC}.

5th Test (After Intervening)			4th Test (after intervening)			3rd Test (Before Intervening)			2nd Test (Before Intervening)			1st Test (Before Intervening)			Test Points Test Periods
C	B	A	C	B	A	C	B	A	C	B	A	C	B	A	
25	26.5	36	23	24	27.5	30	30	33	25.5	26	25	36	37	38.5	23th June
25	26	35	23	24	28	29.5	30	33	25.5	26	27	36	37	38	28th June
25	26	35.5	22	24	27.5	29	29	32	25	25.5	27	37	36.5	37	30th June
24.5	26	35	23	24	29	29	29.5	33	25	25.5	26	36.5	36.5	38.5	5th July
24.5	25.5	34	22	23	28	30	31	34	24.5	25	26.5	36	37	37.5	8th July
24.5	26	34	22	23	28	30	31	33.5	24.5	25	26	35	36.5	38.5	10th July
24	26	35.5	22.5	23.5	27	29	29.5	33	24	24.5	27	35.5	36	38	13th July
24	26	35.5	22.5	24	28.5	29.5	30	33	24.5	25	27.5	36	36	37.5	21th July
24	26.5	35.5	22.5	24.5	28.5	29.5	30	32.5	24	24.5	26	36.5	36	39	27th July
25	26	35	23	23	28	30.5	30.5	33	24.5	25	26	36.5	37	38	2nd August
24	25	35	22	23	28	29	30	33	23.5	24	26.5	36	36.5	37	4th August
24	26	34	22	23	28	29	29.5	33	23.5	24	27.5	35	36	38	10th August

Table 2. Thermometry Assays in Test's Points when the Outdoor Temperature was 36^{oC}. All Units are in ^{oC}.

Experimental Tests	Position A	Position B	Position C
1st Test (Before Intervening)	38	36.5	36
2nd Test (Before Intervening)	26.5	25	24.5
3rd Test (Before Intervening)	33	30	29.5
4th Test (After Intervening)	28	23.5	22.5
5th Test (After Intervening)	35	26	24.5

It is notable that there was no opening near the test-diffuser. As showed in Fig. 11, the test points (A, B, & C) were marked on the test rod. Point of A was leveled with the bottom of the hanged test partition and point of B was leveled with the personnel's face (in work position). All tests were experimented in summer of 2011 when the outdoor temperature was 36^{oC} (registered by a thermometer that was set outdoor in a shady place to assay and register outdoor temperature). All experimental tests were done in several different conditions and the results (daily and total average of thermal experiments in test's points) are presented in table 1 and 2. The different conditions of the experimental tests are listed as follow:

- First experiment (before intervening): all ventilating devices are off and the openings are open.
- Second experiment (before intervening): all ventilating devices are on and the openings are close.
- Third experiment (before intervening): all ventilating devices are on and the openings are open.
- 4th experiment (after intervening): all ventilating devices are on and the openings are close.
- 5th experiment (after intervening): all ventilating devices are on and the openings are open.

It should be noted that all tests were done in 12 days of June (23th, 28th, 30th), July (5th, 8th, 10th, 13th, 21th, 27th), and August (2nd, 4th, 10th). The average of data was calculated and registered in table 2 and demonstrated in Fig. 13. Following Fig. 13, the vertical temperature gradients in 2nd and 4th tests are comparative. The vertical temperature gradients in 3rd and 5th tests are comparative, too.

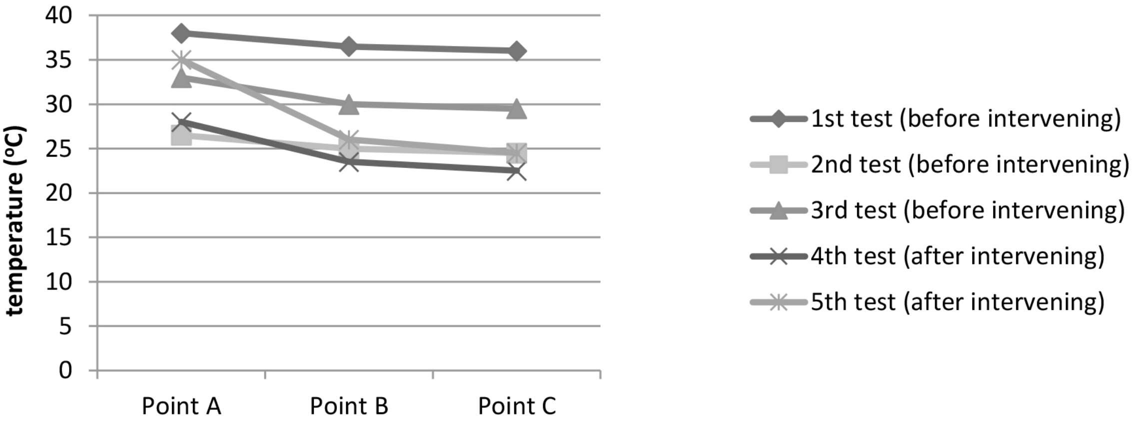


Fig. 13. The Comparative Diagram of Experimental Thermometry Tests in Case Study

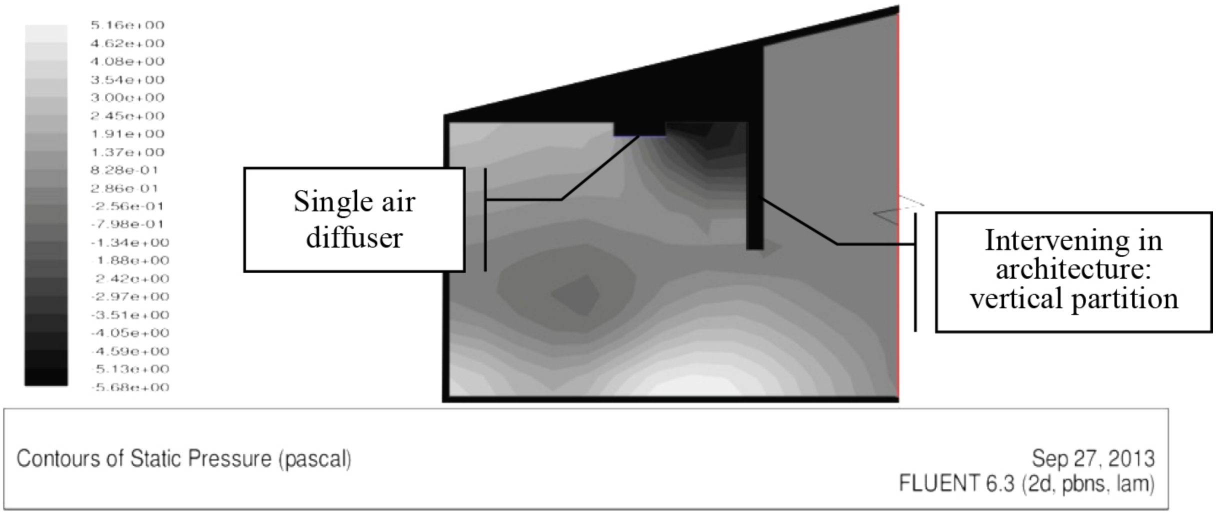


Fig. 14. The Comparative Diagram of Experimental Thermometry Tests in Case Study

Fig.13 demonstrates that after intervening in architecture, the vertical temperature gradients were increased in all tests. After intervening in architecture, the contours of static pressure calculated and simulated with Fluent and demonstrated in Fig. 14. The contours showed that in workplace there is no sensible differential pressure. Just in middle space of the workshop, in higher levels (higher than 3m), there is a low pressure area that is not important. To confirm the experimental tests, a survey (an interview with personnel) was made. Many of the staff was satisfied for intervening and thought that it could be a good solution for cooling problems (Fig 6 and 7, left). In Iran's Electrical Tools factory, it was proposed that by conducting cool air (it can be produced by a water-cooler) with a handmade canal over the work place, a kind of retrofitted hybrid MVS could be made. It was proposed that the air diffuser, inject the cool air right toward the ground at the level of +2.5m high from ground code. The proposed duct & its diffuser were installed and the personnel were pleased for the solution. The experimental tests show that a medial method for air conditioning is better than common MVS and DVS. The proposed way for Iran's Electrical Tools factory is a medial way and the upgraded existing MVS in hygienic production's plant, is a medial method too. Both proposed systems are more effective and the personnel confirmed them.

ECHONIMICAL ANALYSES

The overall heat load generated in the room is 1426 kW. About 1410 kW emitted from manufacturing equipment, about 9 kW from lighting equipment (including 150 fluorescent lamps), and the remaining 7 kW from the 35 operators manning in average the department. In order to achieve the desired environmental conditions in the summer period (air temperature comprised between 24^{oC} and 26^{oC} and 40–60% relative humidity, according to all standards), cooling air has to be injected at a much lower temperature (about $13–14^{oC}$) causing a great energy expenditure of the refrigeration plant (before intervening). In high-ceiling buildings this also means that a large percentage of the room volume in the upper section gets unnecessarily conditioned further increasing the energy expenditure. It can be concluded that in this application the entire volume at height greater than 3 m, is unnecessarily conditioned (see Fig. 1). All of the lights are installed in the ceiling and about a half of equipment that generates heat, are above the workers (higher than +2.5m). However the generated heat in higher levels of the workshop (above the workers) is more than 800kw that is not necessary to cool. So it could be realized that how much frugality would be achieved, because of 3 reasons: 1) just cooling of the one third of the indoor air volume in necessary, 2) there is no need to cool the overload heating of the equipment above the workers, 3) the suddenly discharge of cooled indoor air will not occurred (according to experiments and interviews) if the gates left open.

Before intervening in case study, whereas the MVS was usually off and because of the private sector's problems, alterations in annually energy consumptions were done, it was not possible to compare periodic energy consumption. Nevertheless the chillers' electric power consumption (4 chillers for whole of the plant) in test's period was measured. It was realized that the electric power consumption before intervention was about 4200kw (maximum power), however after intervening it was reduced to 3350kw. So with this method, about 20% frugality in energy consumption was occurred.

CONCLUSION

The experimental tests shows that a retrofitted system operated between MVS and DVS is more effective, because the vertical temperature gradient in the lower part of the room is under control (contrary to DVS) and the thermal comfort in workplace with no need to air conditioning all indoor air volume, is achievable (contrary to MVS). Furthermore much frugality in energy consumption would be achieved through this method (according to this study) because there is no need to cool the upper part of the workplace and restoration of overloaded heating of the above equipment.

Following the experimental tests, if the injection of cool air is carried out right toward the ground at level of +2.5m or +3.0m high from ground code (no matter the height of indoor space) and the warm air exhausts from grilles located at floor level, a proper vertical temperature gradient would be made and the comfort condition in workers level could be established in indoor airflow's path (no matter the height of ceiling's status). In this case if the gates keep open, the comfort condition in workplace could be maintained and in the worker's level, the alteration in air temperature would be inappreciable while the temperature of the upper part of the salon could be as warm as the outdoor or more; that is not important. This enables to increase the cooling air temperature thus reducing the power consumption of the cooling plant to gain substantial savings. So as mentioned in chapter 8, there is no need to consume more energy to cool the upper parts and it could be realized that how much frugality in energy consumption would be achieved. This result note that the new method presented in this research, is more economic and the comfort condition in worker's level is more durable. So here some suggestions are recommended:

1. A proposal section for industrial buildings can be like Fig. 16. The height of the short part is about 3m (no matter the height of saloon) and the diffusers must be installed like Fig. 16.
2. An improved retrofitted hybrid MVS is more effective than existing MVS or DVS. So to improve existing MVS, it's necessary to use just lateral air diffusers near the sidewalls and install a vertical partition hanged from the ceiling; like what was done in this research. In this method, the cooled air would not be wasted to cool the middle parts of workshop (no matter the salon's height). Just the height level of the lower part of the hanged partition is important (about 3m). A schematic diagram can be presented as Fig. 15.
3. A kind of retrofitted hybrid MVS can be made by water-coolers in some plants that have no cooling systems. The method used in Iran's Electrical Tools factory is recommended.

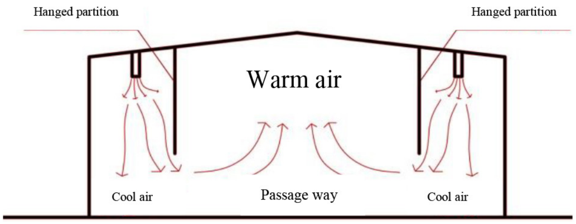


Fig. 15. The Architectural Proposed Section After Intervening

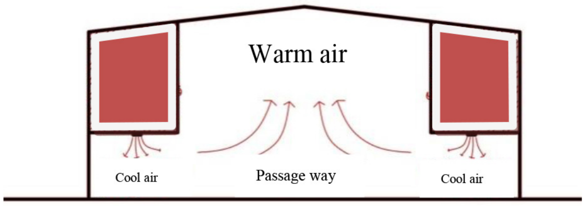


Fig. 16. The Architectural Proposed Section of Industrial Buildings

ENDNOTES

1. The Control of Substances Hazardous to Health
2. Recommended Exposure Level
3. National Institute for Occupational Safety and Health
4. Permissible Exposure Limit
5. Occupational Safety and Health Administration

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