

DATA CENTER AIR COOLING SYSTEM

By

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ABSTRACT OF THE THESIS

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At present, data centers are widely used in computer software companies, banks and so on. It requires a huge amount of electric power to operate these data centers and the majority part of the electric power is used to cool the computer units in the data center, so it is important to study the cooling system of the data centers. Since data centers are becoming bigger and bigger, it is harder to manage the cooling system of the data center. Air-cooling systems are inefficient in emergency cases. In this research, the influence of air-cooling system performance by inlet temperature, inlet velocity and the heat output of the computer units are examined. A data center with raised floor air-cooling system is adopted. Ansys 12.0 is used to simulate the thermodynamic conditions of the data center at different situations. It is concluded that, the inlet temperature directly affects the maximum temperature of the data center. For every one degree the inlet temperature

lowered, the maximum temperature of the data center will be lowered by 0.487 degree. Because it is economically infeasible to lower the inlet temperature to a large extent, it is not a good method to cool the data center in emergency cases. The heat output of computer units is also directly proportional to the maximum temperature of the data center. When the heat output increases by 1000 W/m^3 , the maximum temperature of the data center will be increased by almost 80 degrees. The heat output of the computer units increases several thousand watts per cubic meter in a short period for emergency cases. It is very important to control the heat output of the computer units, otherwise, an air-cooling system just cannot control the temperature. Simply increasing the inlet velocity will not help cooling the computer units. Every computer unit has its own best inlet velocity based on its positions.

Acknowledgements.

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NOMENCLATURE

K_{eff}	Effective neutron multiplication factor
V	Velocity
E	Energy per unit mass
ρ	Density
t	Time
T	Temperature
h_j	Diffusion coefficient of the specie
S_h	Volumetric energy source
J_j	Diffusion flux of species
τ_{eff}	Effective Viscous Dissipation factor
P	Pressure
Re	Reynolds Number
D_H	Hydraulic diameter
Q	Computer unit heat output
ν	Viscosity
P_w	Wetted perimeter of the cross-section.
P_k	Generation of turbulence kinetic energy due to the mean velocity

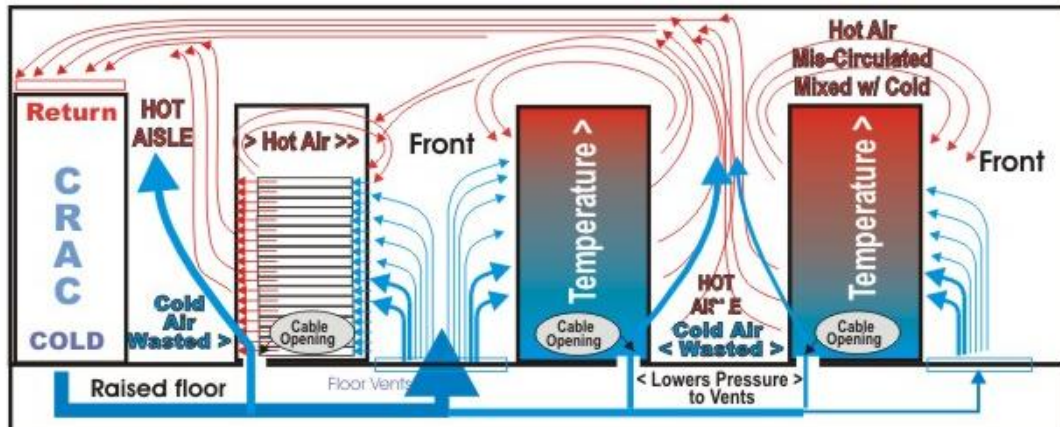
	gradients
P_b	Generation of turbulence kinetic energy due to buoyancy
Y_M	Contribution of the fluctuating dilatation in compressible turbulence
$C_2, C_{1\epsilon}$ and $C_{3\epsilon}$	Constants
σ_k and σ_ϵ	Turbulent Prandtl numbers
S_k and S_ϵ	User defined source terms

I. Introduction

A Data center is a facility that supplies a feasible environment for internet and computer devices. It is also named as data processing equipment (DPE) , it has a significant meaning for banking, scientific computing, cloud computing technologies and so on [1]. At present, accompanied by the rapid development of computer science and internet technologies, data centers are becoming larger and larger. Large data centers sometimes contain thousands of racks while there are several different kinds of computer units in each rack. Each computer unit dissipates about 250 W of power, and the whole rack can dissipate 10 KW of power. In the near future, a 100000 square foot data center may require 50 MW of power to operate and an additional power of 20 MW will be lost as heat. Even a much smaller data center with 5000 10KW racks will need 44M dollars a year to keep running [2]. For a classical data center, around 60 to 70 percent of power is consumed by the cooling system. It is very important to research the cooling system of the data center to help minimize the operating cost [3]. Most of the data centers use the raised-floor air cooling system since this system helps balancing the airflow distribution which is very important for the air cooling of the data center [4]. Figure 1 shows a typical layout of a raised-floor air cooling system[5].

In this paper, Ansys 12.0 is used to simulate the thermodynamic condition of a data center with four racks, each with 2 computer units. A typical 2D raised-floor air cooling layout is introduced and steady state is assumed. The influence of air cooling performance by inlet velocity, inlet temperature and heating source power (Q) is researched.

Fig 1, A Typical raised-floor air cooling system [5]



II, Data center configuration.

1) Configuration and setup.

This study only considers two dimensional cases. After mesh and aspect ratio checks, the final data center configuration shown in figure 1 is chosen. The process will be introduced later in the paper. The data center is set up in a room with width of 24m and height of 3m. There are four racks in the room, each with a width of 0.5m and a height of 1.5m. In each rack, there are two computer units and three fans, each with a height of 0.3m. There are four inlets on the bottom of the room, each with a width of 0.25m. The only outlet is located on the right side wall, 1.5m above ground, the height of the outlet is 0.5m. Their values are chosen as representative of a typical data center.

This configuration simulates the most commonly used design of a data center at present. The computer room air-conditioning units (CRAC) with raised floor layout. From figure 1, it is easy to see that this design minimizes the interference between the inlet cold air and the hot air blown out by the fans. This is a key feature that helps the data center performing better in air cooling.

The computer simulations in this project are performed by the software Ansys 12.0 (Fluent). The computer units are set up to be made of ceramic, with density of 4000kg/m^3 , Specific heat of 775J/kg-K and thermal conductivity of 30 W/m-K . The properties of materials that used to produce real computer units are very close to ceramic, so the values are appropriate. For the fluid, air with density of 1.225 kg/m^3 , specific heat of 1006.43 J/kg-K , thermal conductivity of 0.0242 W/m-K and viscosity of $1.7894\times$

10^{-5} kg/m-s is used. Since these properties of air will not change severely for the conditions of this project, it is appropriate to set them as constant.

2) Important models and equations.

There are two major models used to perform the simulations in Fluent for this project: Energy model and K-epsilon model.

In ansys 12.0, the energy model contains two major equations:

1, Energy transportation equation[6]:

$$\frac{\partial(\rho E)}{\partial t} + \nabla \cdot [V(\rho E + \rho)] = \nabla \left[K_{eff} \nabla T - \sum_j h_j J_i + \tau_{eff} \cdot V \right] + S_h$$

This is a basic thermodynamic equation. The first term of this equation is the unsteady term. For this study, steady state condition is assumed, so term 1 is equal to zero.

2) Energy per unit mass is defined as [6]:

$$E = h - \frac{P}{\rho} + \frac{V^2}{2}$$

In this project, a realizable k-epsilon model is used to simulate the transport phenomena. The transportation equations are [7]:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + P_K + P_B - \rho \epsilon - Y_M + S_k$$

$$\frac{\partial}{\partial t}(\rho \epsilon) + \frac{\partial}{\partial x_j}(\rho \epsilon u_j) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] + \rho C_1 S_\epsilon - \rho C_2 \frac{\epsilon^2}{k + \sqrt{\nu \epsilon}} + C_{1\epsilon} \frac{\epsilon}{k} C_{3\epsilon} P_b + S_\epsilon$$

Where

$$C_1 = \max \left[0.43, \frac{\eta}{\eta + 5} \right], \eta = S \frac{k}{\epsilon}, S = \sqrt{2S_{ij}S_{ij}}$$

In the study, the equation [8]:

$$Re = \frac{VD_H}{\nu}$$

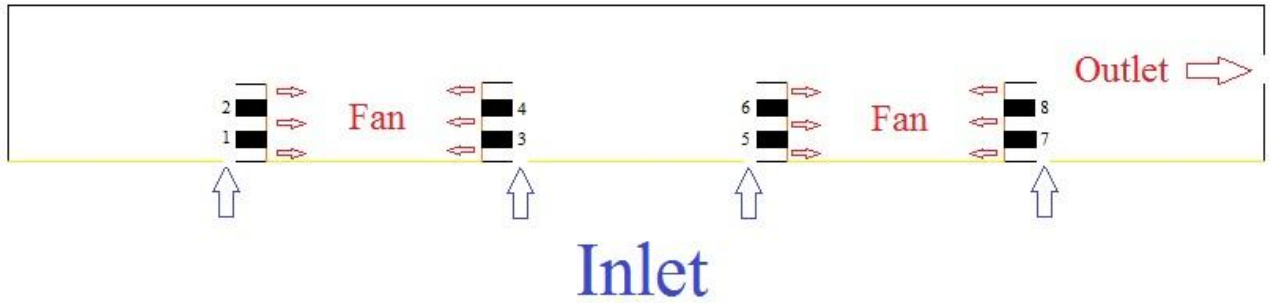
where

$$D_H = \frac{4A}{P_w}$$

is used to represent inlet conditions as the dimensionless quantity Reynolds number.

Fig 2, Chosen Configuration

Room:width=24m; height=3m
 Rack:width=0.5m; height=1.5m
 Inlet width=0.25m
 Outlet (1.5m above the ground):height=1.5m
 Fan(marked by orange lines):height=0.3m
 Computer unit (area filled with black):width=0.5m; height=0.3m
 Floor (marked by yellow lines):width=4.2m



III, Grid Reinforcement.

The mesh check is very important for this project, it is used to determine if the mesh is dense enough to give accurate results. This is the first step of this study. For the mesh check, the configuration is similar to the final configuration, but with an aspect ratio of 7 to 3 (7m in width, 3m in height) and a inlet width of 1m. The inlet temperature was set as 293K, the inlet velocity equals to 3m/s ($Re=191326$). The computer unit was set up to be a heating source with heat output equals to $2000W/m^3$, and the pressure difference of the fan was set up to be 100Pa. In the grid reinforcement, it is found that 0.025m per mesh in width and 0.0125m per mesh in height is accurate enough. Table 1 shows the mesh check result, points 1,2,3,4,5,6,7,8 are the middle points of computer units. As the result of mesh check, for the final configuration with width of 24m and height of 3m, the 960x240 mesh is used.

In the grid reinforcement, it is also found that the velocity of the air was much too high inside the data center (maximum velocity was near 20m/s). Because of that, in the next step, the inlet width, the pressure difference of fans and the inlet velocity were reduced. It is also found that, with heat output equals to $2000W/m^3$, air cooling system cannot cool the data center efficiently, so the heat output was decreased to $1000W/m^3$ for the aspect ratio check.

Fig 3, Position of points 1,2,3,4,5,6,7,8

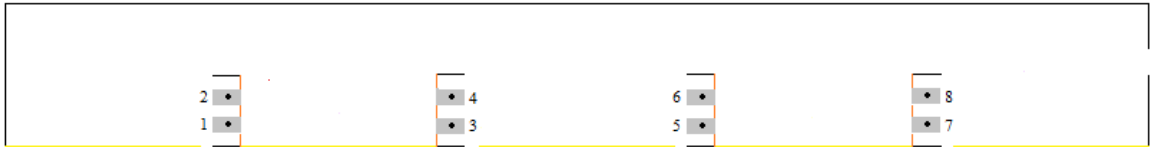


Table 1, Grid reinforcement

	280x240 Point Temperature (K)	420x360 Point Temperature (K)	Difference Rate
			$\frac{\text{Temperature difference}}{\text{Highest temperature} - \text{lowest Temperature}}$
point1	329.857	328.729	-0.020155814
point2	321.875	322.06	0.003305697
point3	360.852	360.402	-0.008040883
point4	334.678	334.717	0.000696877
point5	338.268	337.405	-0.015420628
point6	322.516	322.563	0.000839826
point7	377.839	377.042	-0.014241298
point8	366.467	366.226	-0.00430634

IV, Aspect ratio check

The aspect ratio of the room is also a key feature of the final configuration. It seriously influences the result. The aspect ratio of 3:1 (9 meters in width, 3 meters in height), 4:1 (12 meters in width, 3 meters in height) and 8:1 (24 meters in width, 3 meters in height) were tested. Based on the experience gained in the mesh check process, the inlet temperature of the air was set to be 298K, the inlet width was set to be 0.25m, the inlet velocity was set to be 0.376m/s ($Re=6000$). The computer units were set up to be a heating source with heat output of $1000W/m^3$ and the pressure difference of the fans were set up to be 10Pa.

The 3:1 aspect ratio is not perfect, the room is too small. The interference between the air flows is dramatic. The air cooling efficiency is low. the maximum temperature is close to 390K, This temperature will seriously influence the performance of the computer units.

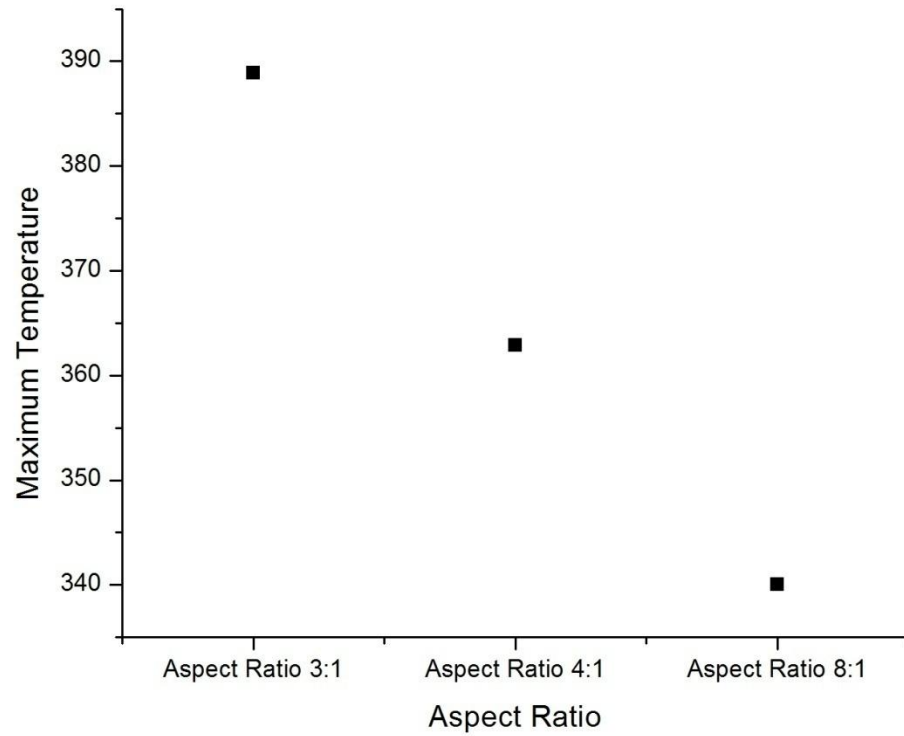
The case with aspect ratio of 4:1 performs much better. The maximum temperature is around 363K. It is in a acceptable range. There are maybe two reasons why the case with aspect ratio of 4:1 performs better: 1) The interference between air flows is not as significant as the 3:1 aspect ratio case. 2) A bigger room can absorb more heat.

The case with aspect ratio of 8:1 is the best choice, with a maximum temperature of only 340K. This aspect ratio really helps the air cooling of the racks. The aspect ratio check shows that the interference of air flows seriously influence the performance of air

cooling. It is important to separate the cold air flow and hot air flow. A larger environment also helps the performance of air cooling.

The air velocity in the data center is still higher than normal in aspect ratio check process (around 5m/s). To solve that, the pressure difference of the fan is lowered to 3pa in the final cases. The 1000W/m^3 heat output seems still too high for air-cooling system to control, so for the final cases, 400W/m^3 to 800W/m^3 heat outputs are used.

Fig 4, Maximum Temperature at aspect ratios 3:1, 4:1 and 8:1



V, Simulation.

After the aspect ratio and mesh checks, the final configuration was chose. To research the influence of air cooling performance by inlet temperature, inlet velocity (Re) and computer unit heat output (Q) , 9 cases were simulated by ansys 12.0:

Inlet velocity (Re) group:

Inlet Temperature= 298K, Inlet velocity=0.507m/s (Re=8000), Q=800 w/m³.

Inlet Temperature= 298K, Inlet velocity=0.627m/s (Re=10000), Q=800 w/m³.

Inlet Temperature= 298K, Inlet velocity=0.753m/s (Re=12000), Q=800 w/m³.

Inlet temperature group:

Inlet Temperature= 288K, Inlet velocity=0.376m/s (Re=6000), Q=800 w/m³.

Inlet Temperature= 293K, Inlet velocity=0.376m/s (Re=6000), Q=800 w/m³.

Inlet Temperature= 298K, Inlet velocity=0.376m/s (Re=6000), Q=800 w/m³.

Inlet Temperature= 303K, Inlet velocity=0.376m/s (Re=6000), Q=800 w/m³.

Heating source output (Q) group:

Inlet Temperature= 298K, Inlet velocity=0.376m/s (Re=6000), Q=400 w/m³.

Inlet Temperature= 298K, Inlet velocity=0.376m/s (Re=6000), Q=600 w/m³.

Inlet Temperature= 298K, Inlet velocity=0.376m/s (Re=6000), Q=800 w/m³.

Sample results are illustrated by the following figures.

Fig 5, Temperature distributions of the case with $Re=6000$, inlet temperature=298K and $Q=800W/m^3$

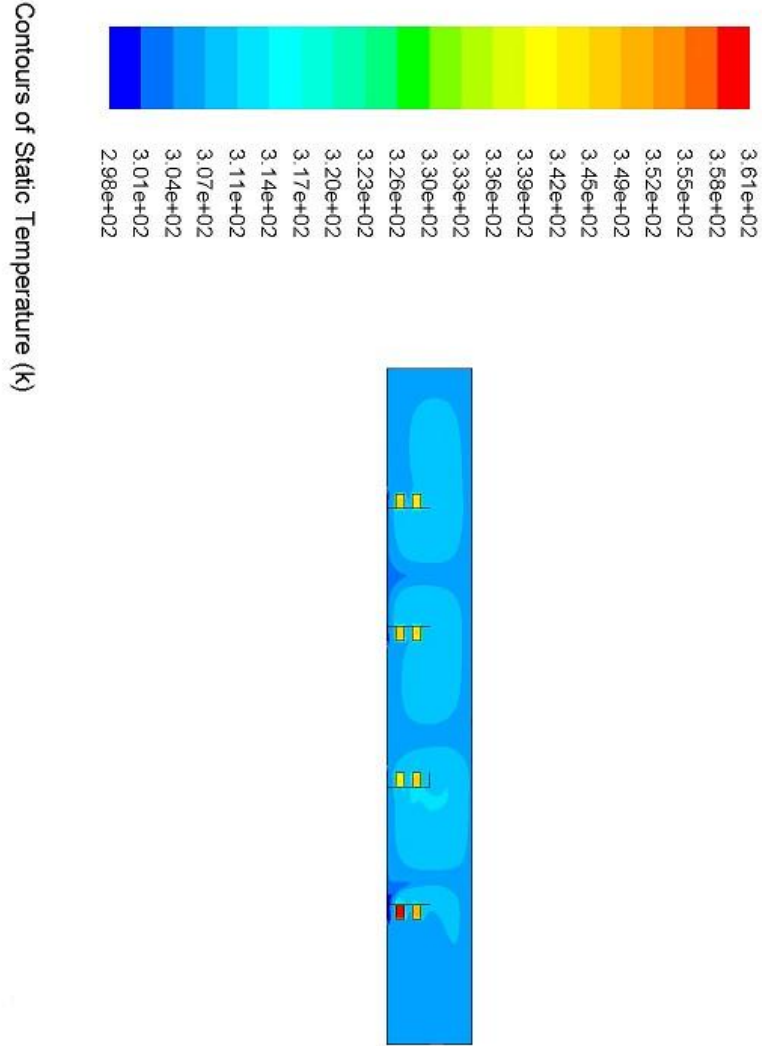


Fig 6, Velocity distributions for the case with $Re=6000$, inlet temperature=298K and $Q=800W/m^3$

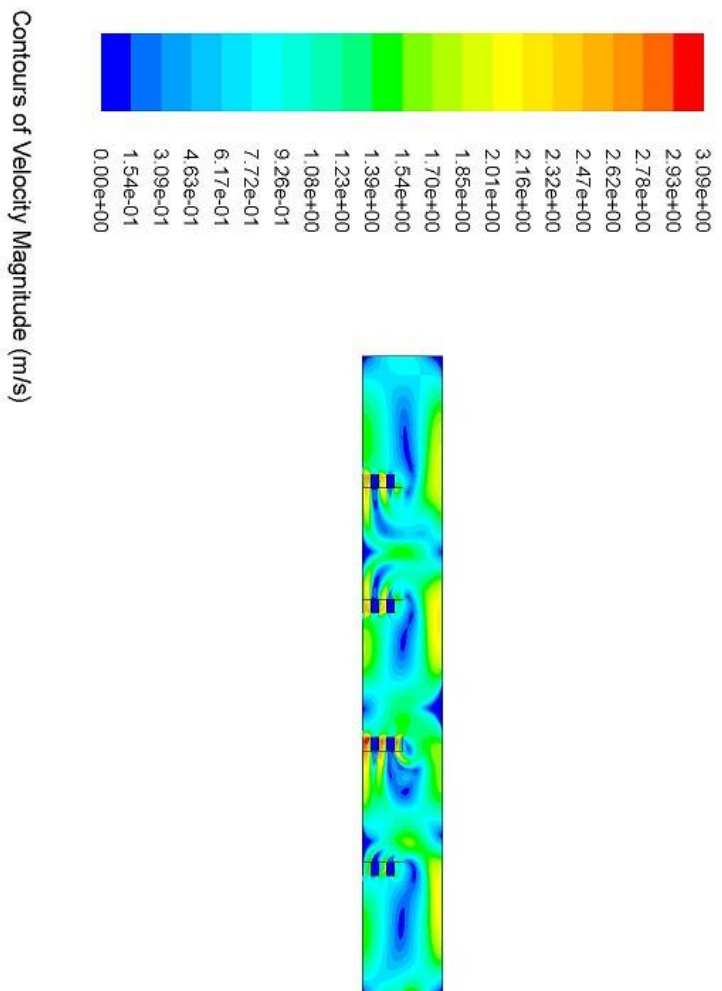


Fig 7, Isotherms for the case with $Re=6000$, inlet temperature= $298K$ and $Q=800W/m^3$

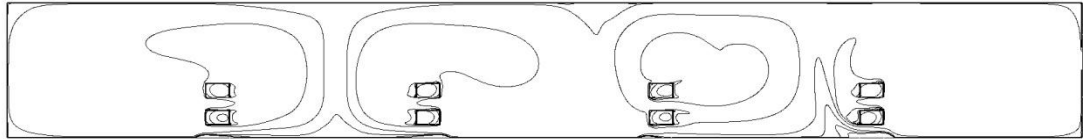


Fig 8, Stream lines for the case with $Re=6000$, inlet temperature= $298K$ and $Q=800W/m^3$

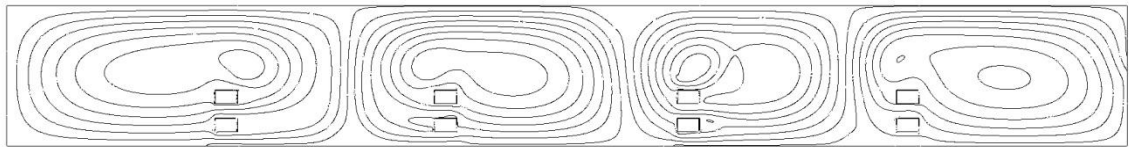


Fig 9, Temperature distributions for the case with $Re=12000$, inlet temperature= $298K$ and $Q=800W/m^3$

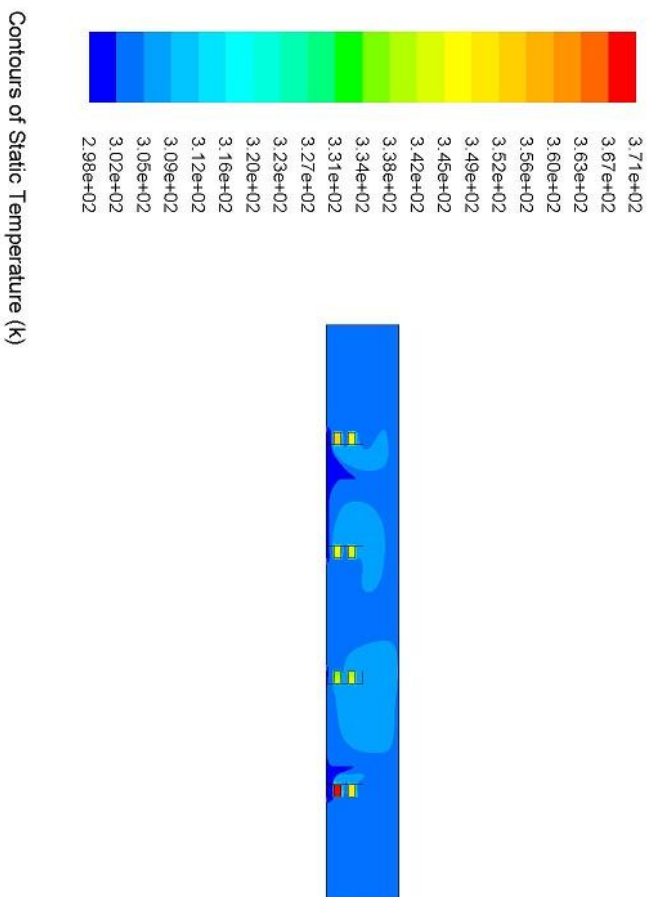


Fig 10, Velocity distributions for the case with $Re=12000$, inlet temperature=298K and $Q=800W/m^3$

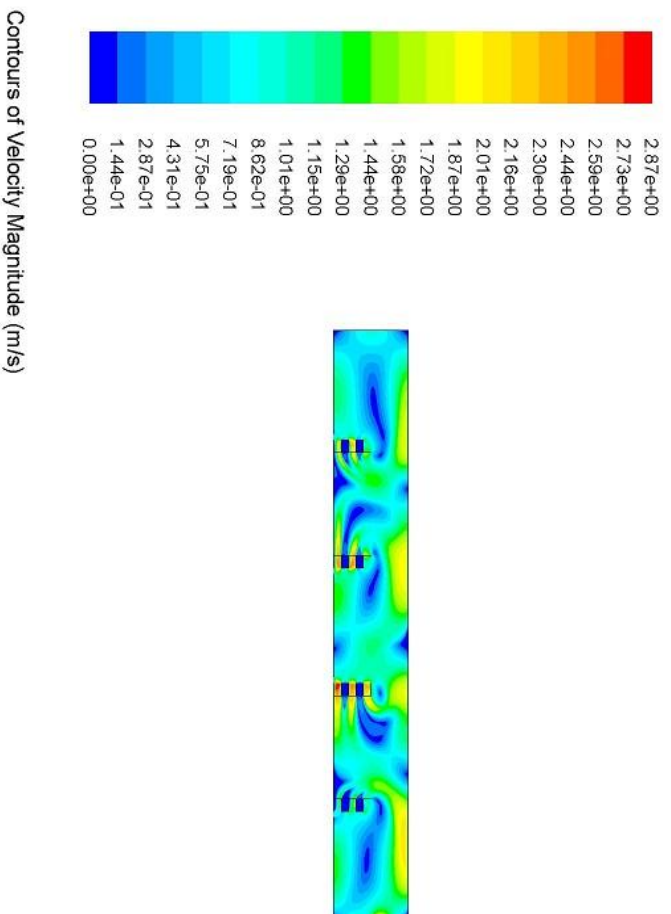


Fig 11, Isotherms for the case with $Re=12000$, inlet temperature= $298K$ and $Q=800W/m^3$

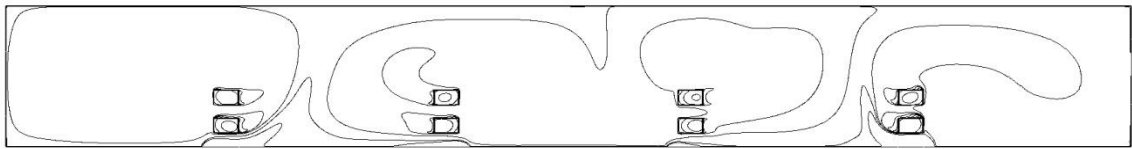


Fig 12, Stream lines for the case with $Re=12000$, inlet temperature= $298K$ and $Q=800W/m^3$

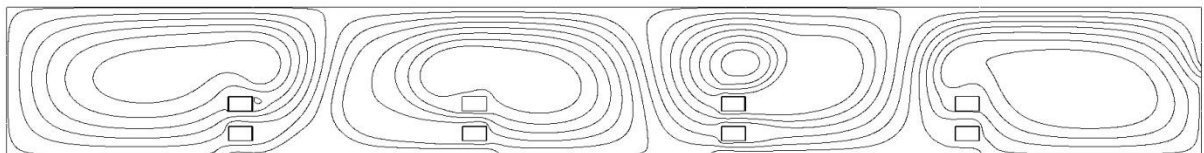


Fig 13, Temperature distributions for the case with $Re=6000$, inlet temperature= $293K$ and $Q=800W/m^3$

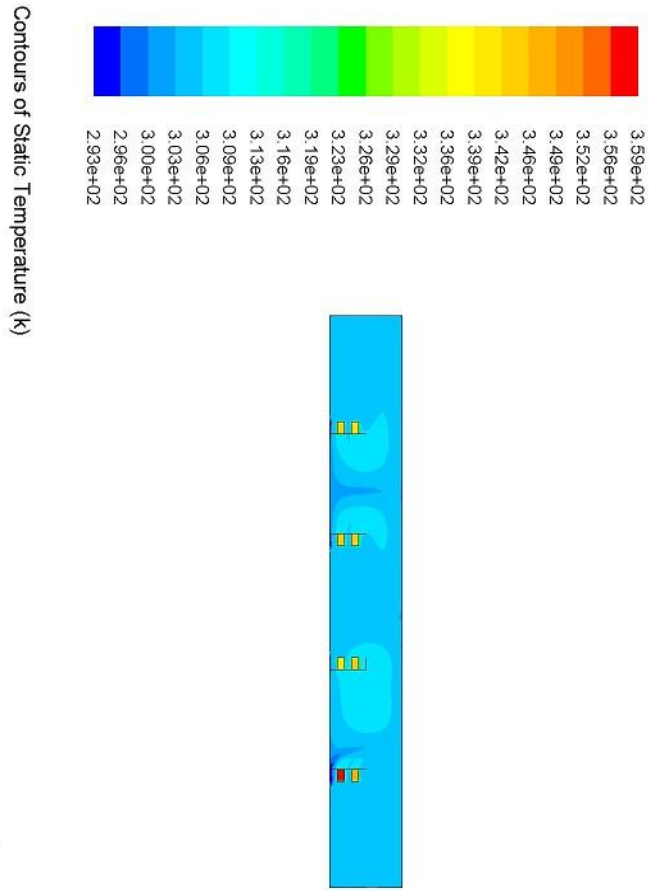


Fig 14, Velocity distributions for the case with $Re=6000$, inlet temperature= $293K$ and $Q=800W/m^3$

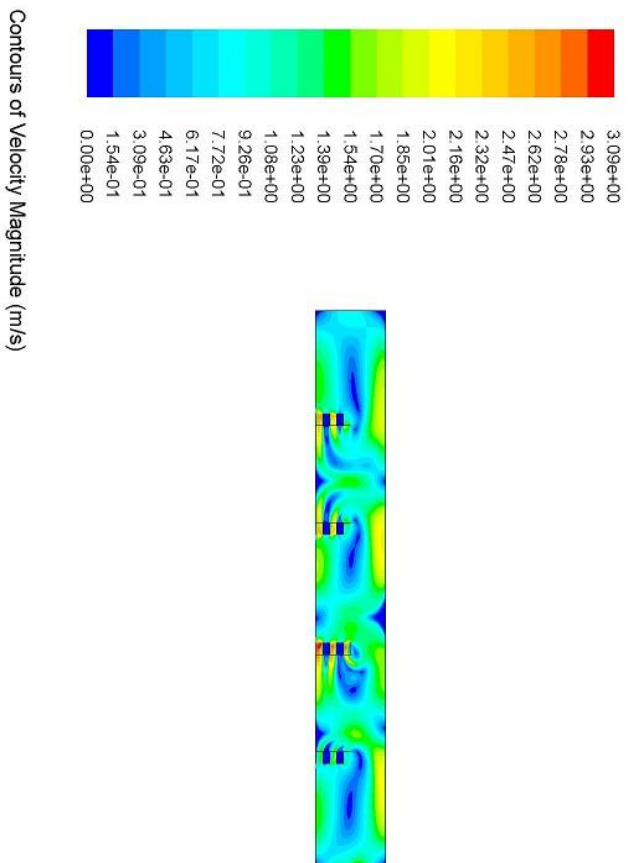


Fig 15, Isotherms for the case with $Re=6000$, inlet temperature= $293K$ and $Q=800W/m^3$

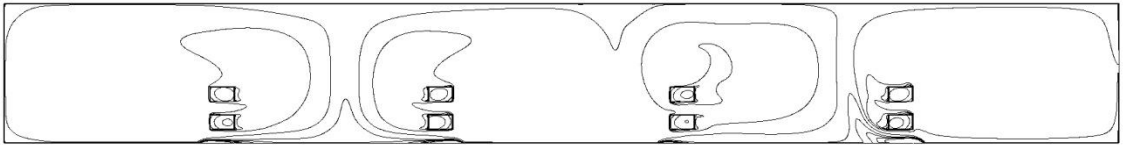


Fig 16, Stream lines for the case with $Re=6000$, inlet temperature= $293K$ and $Q=800W/m^3$

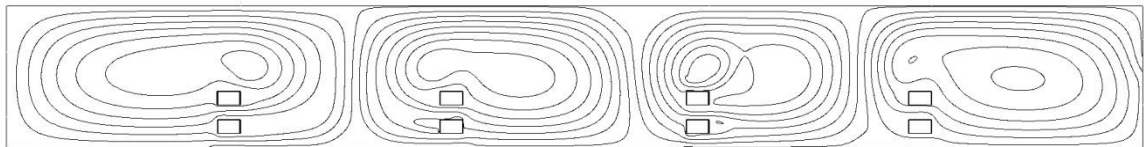


Fig 17, Temperature distributions for the case with $Re=6000$, inlet temperature=293K and $Q=400W/m^3$

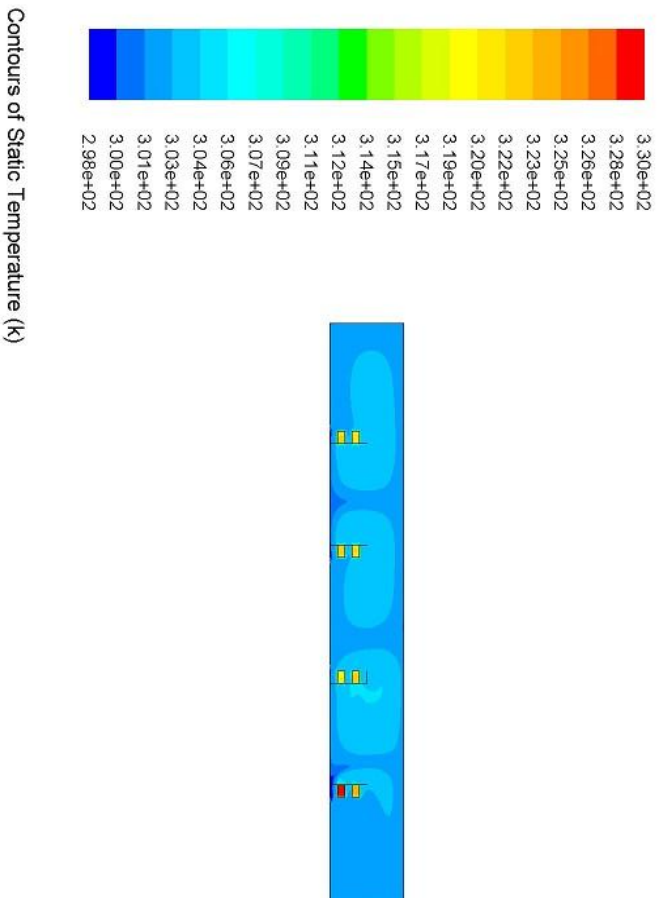


Fig 18, Velocity distributions for the case with $Re=6000$, inlet temperature=293K and $Q=400W/m^3$

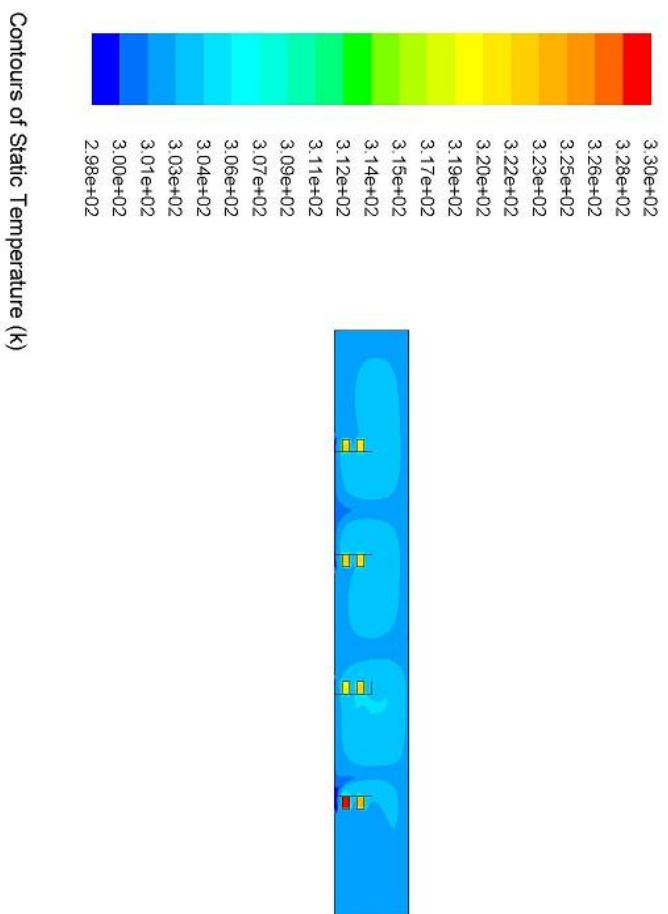


Fig 19, Isotherms for the case with $Re=6000$, inlet temperature= $293K$ and $Q=400W/m^3$

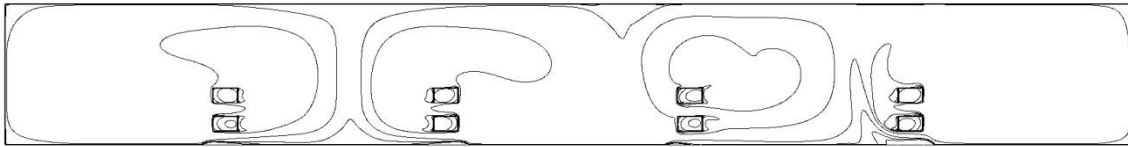
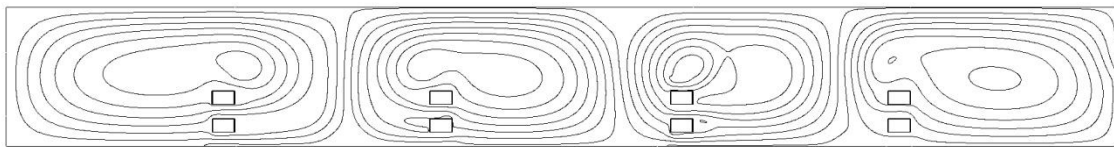


Fig 20, Stream lines for the case with $Re=6000$, inlet temperature= $293K$ and $Q=400W/m^3$



VI, Results

From the results it is clear that, there is a big temperature difference between each computer unit, so they are researched separately (The serial number of computer units are shown in figure 2). All the equations in this section use SI units.

For all the linear fits in this section, adjusted R^2 value and P value were obtained to determine if the linear fits are reasonable. Adjusted R^2 value is a transformation of R^2 value (coefficient of determination) which is used to test if a statistical model is reasonable, the range of adjusted R^2 value is between 0 and 1, generally speaking, a excellent statistical model will have a adjusted R^2 value that very close to 1[9]. The p-value is widely used in the statistical field, for a statistical model, typically a p-value less than 0.05 can help proving the model is proper.

1) Computer unit 1.

The average temperature on the vertical middle plane of computer unit 1 (line 1) was studied. The average temperature of line 1 for all cases is 343.825K. Computer unit 1 ranked No.6 (from lowest average temperature to highest temperature) in air-cooling performance.

There is a linear relationship between the average temperature of line 1 and inlet temperature, the equation obtained from a curve fit is:

$$T_{line\ 1} = 0.42531T_{inlet} + 218.69777$$

The adjusted R^2 value of this linear fitting is almost 1 the P value is 1.86×10^{-6} which is much smaller than 0.05. This means this linear fit is excellent. This equation proves the temperature of line 1 is directly proportion to the inlet temperature.

From this equation, it is concluded that, for every 1degree the inlet temperature lowered, the average temperature of line 1 will decrease 0.425 degree.

The linear relationship between the average temperature of line 1 and computer unit heat output (Q) is also obvious, the equation obtained from a curve fit is:

$$T_{line\ 1} = 0.05934Q + 297.95865$$

The adjusted R^2 of this linear fitting is 1 which means this linear equation tells the exact relationship between the average temperature of line 1 and heating source output.

From this equation, it is clear that for every 1000 W/m³ the computer unit 1 heat output increases, the average temperature of line 1 will increase 59 degrees.

There is no perfect linear relationship between average temperature of line 1 and inlet velocity (Re), but it is clear that the average temperature of line 1 increases while inlet velocity increases. Increasing inlet velocity will not help cooling computer unit 1.

Fig 21, Positions of computer unit 1 and line 1



Fig 22, Average temperature of line 1 vs. inlet Temperature

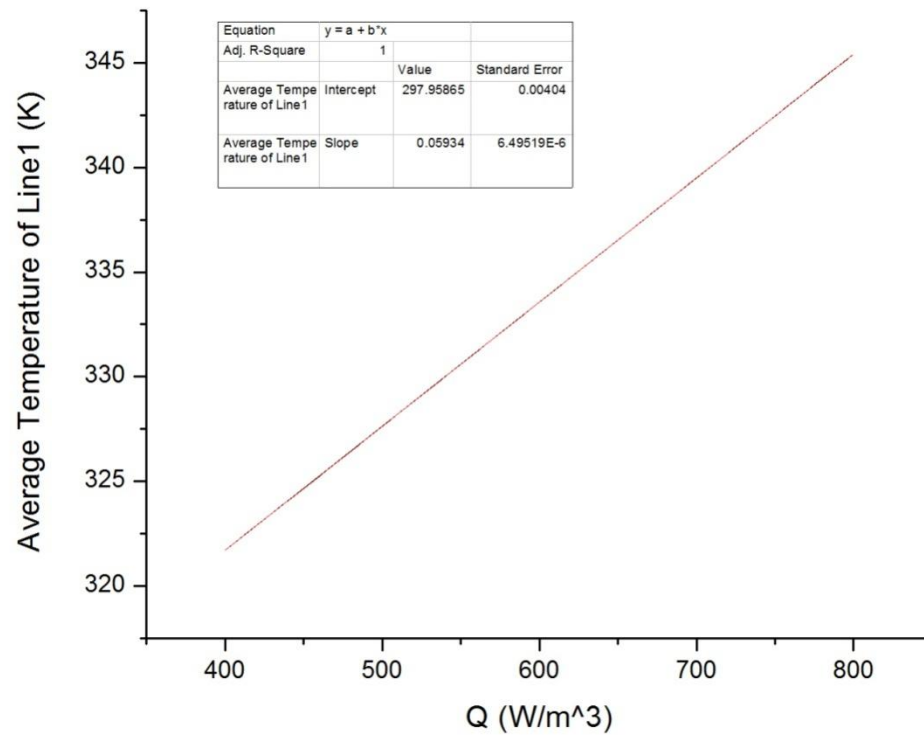


Table 2, Analysis of variance for linear fit in Fig 22

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	22.61107	22.61107	538134.6942	1.86E-06
Error	2	8.40E-05	4.20E-05		
Total	3	22.61116			

Fig 23, Average temperature of line 1 vs. Q

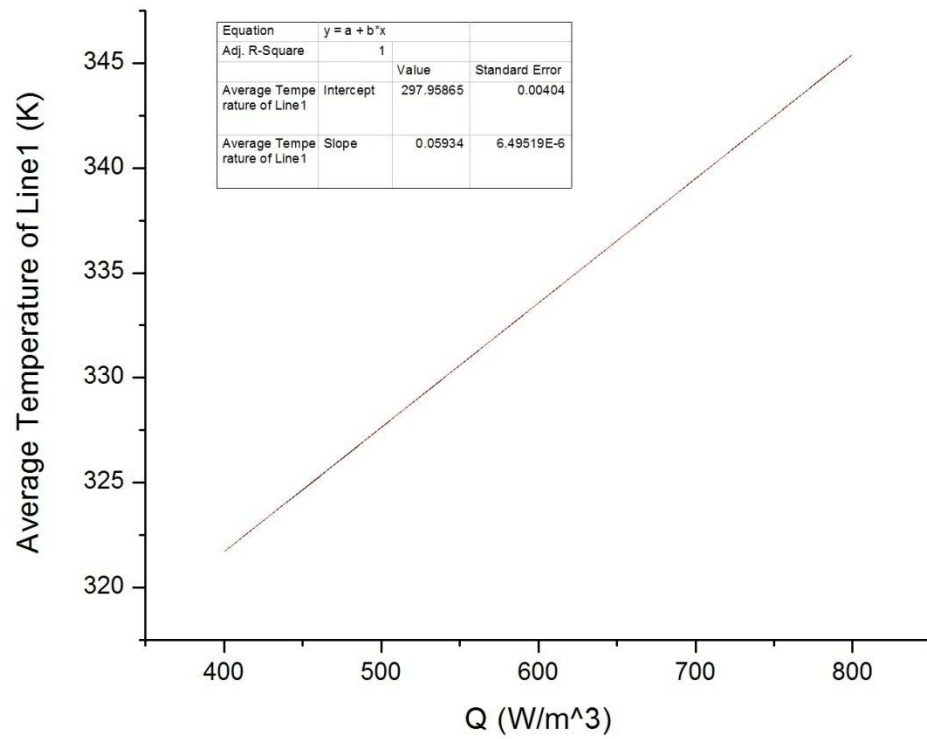
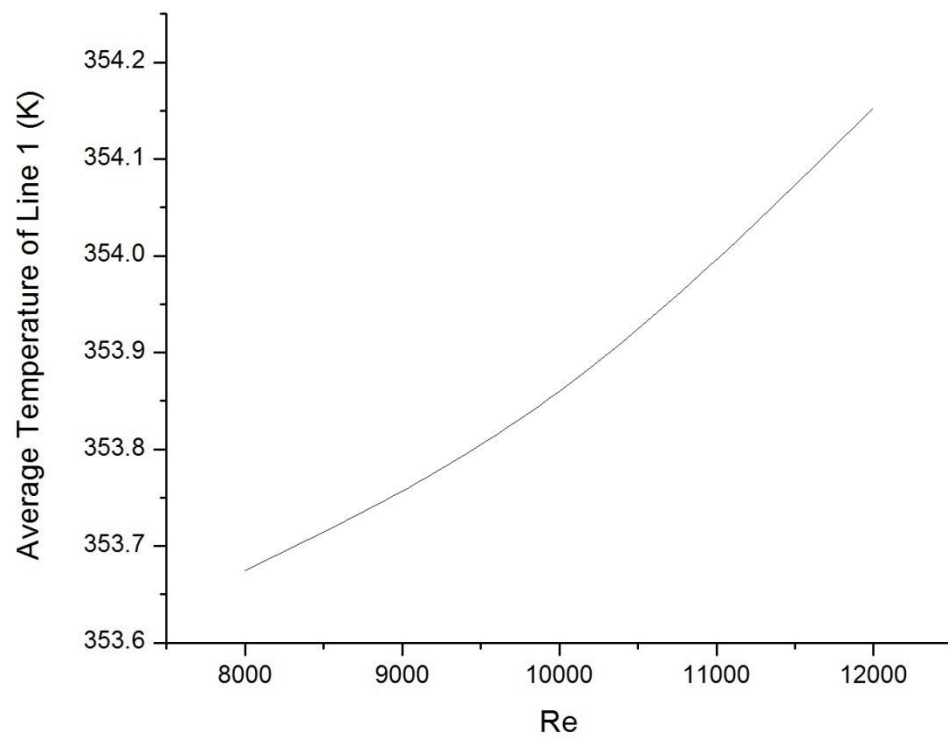


Table 3, Analysis of variance for linear fit in Fig 23

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	281.71546	281.71546	8.35E+07	6.97E-05
Error	1	3.38E-06	3.38E-06		
Total	2	281.71547			

Fig 24, Average temperature of line 1 vs. Re



2) Computer unit 2.

For computer unit 2, the average temperature on the vertical middle plane (line 2) was studied. The average temperature of computer unit 2 for all cases is 339.69K. Computer unit 2 ranked No. 3 (from lowest average temperature to highest average temperature) in air-cooling performance.

The linear relationship between the average temperature of line 2 and inlet temperature is excellent. The equation obtained from a curve fit is:

$$T_{line2} = 0.43721T_{inlet} + 212.74627$$

The adjust R^2 value of this linear fit is almost 1, and the P value is 2.82×10^{-6} which is tiny. These prove the linear fit is perfect.

This linear fit tells that, if the inlet temperature decreases 1 degree, the average temperature of line 2 will be lowered 0.437 degree.

There is a perfect linear relationship between the average temperature of line 2 and computer unit heat output (Q). The equation obtained from a curve fit is:

$$T_{line2} = 0.05634Q + 297.95417$$

For this linear fit, the adjusted R^2 is very close to 1 and P equals 3.26×10^{-5} , these prove the linear fitting is very reasonable.

From this linear fit, it is concluded that, the average temperature of line 2 will increase 56 degrees, while the heat output of computer unit 2 increases 1000 W/m³

The average temperature of line 2 decreases, when inlet velocity (Re) increases. Increasing inlet velocity may help cooling computer unit 2.

Fig 25, Positions of computer unit 2 and line 2

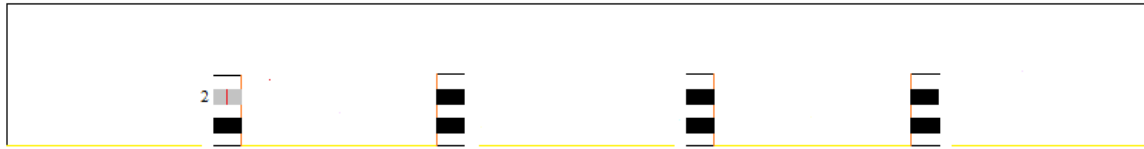


Fig 26, Average temperature of line 2 vs. inlet Temperature

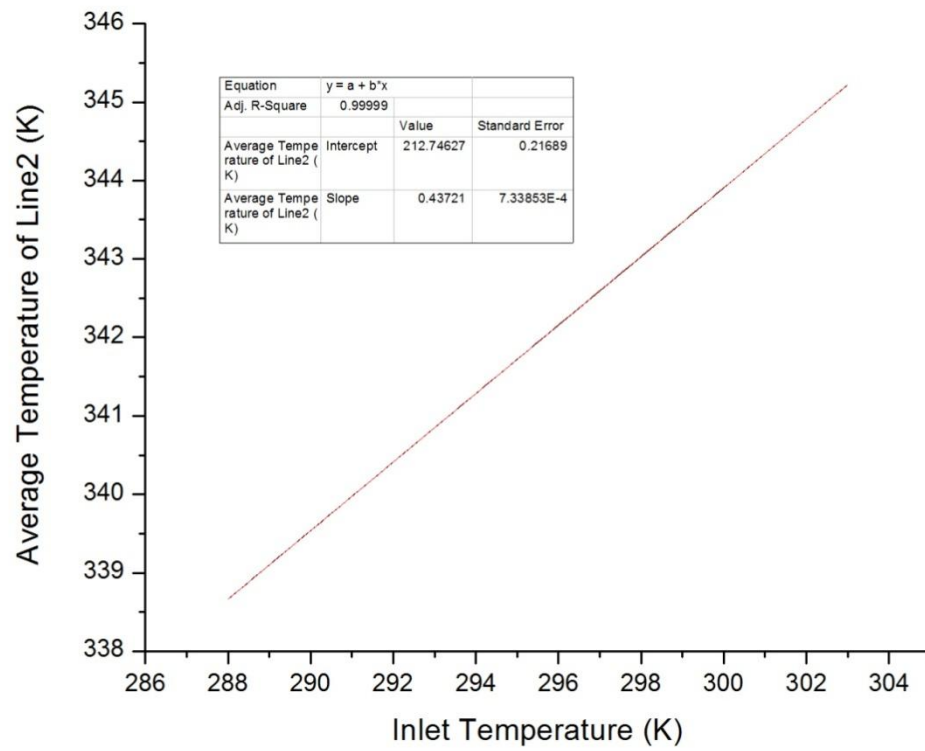


Table 4, Analysis of variance for the linear fit in Fig 26

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	23.89407	23.89407	354945.9	2.82E-06
Error	2	1.35E-04	6.73E-05		
Total	3	23.89421			

Fig 27, Average temperature of line 2 vs. Q

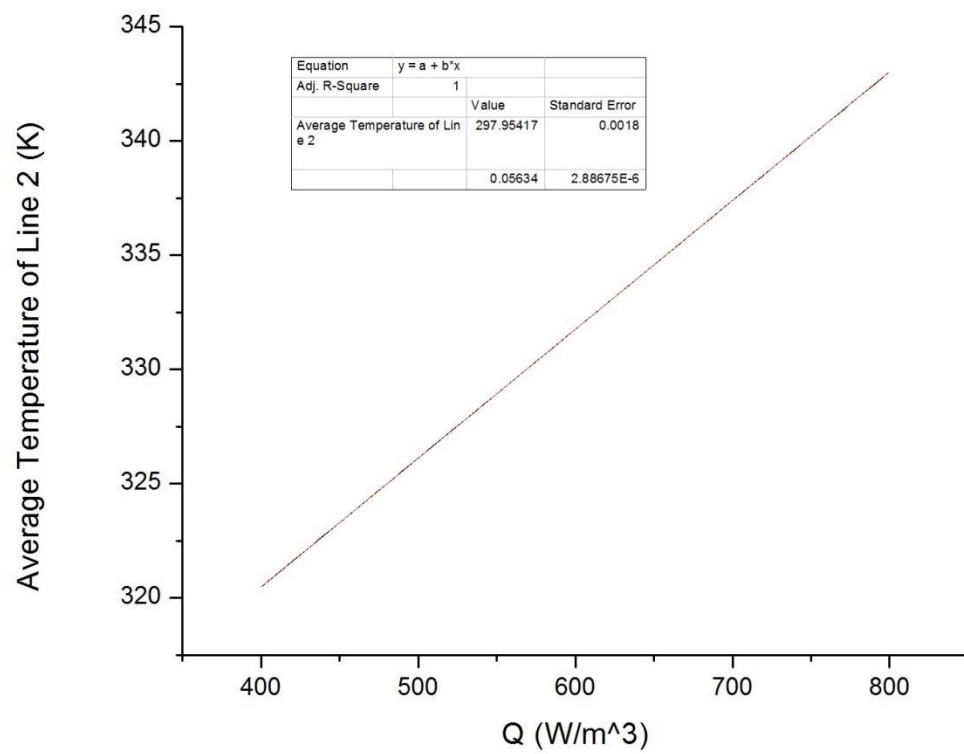
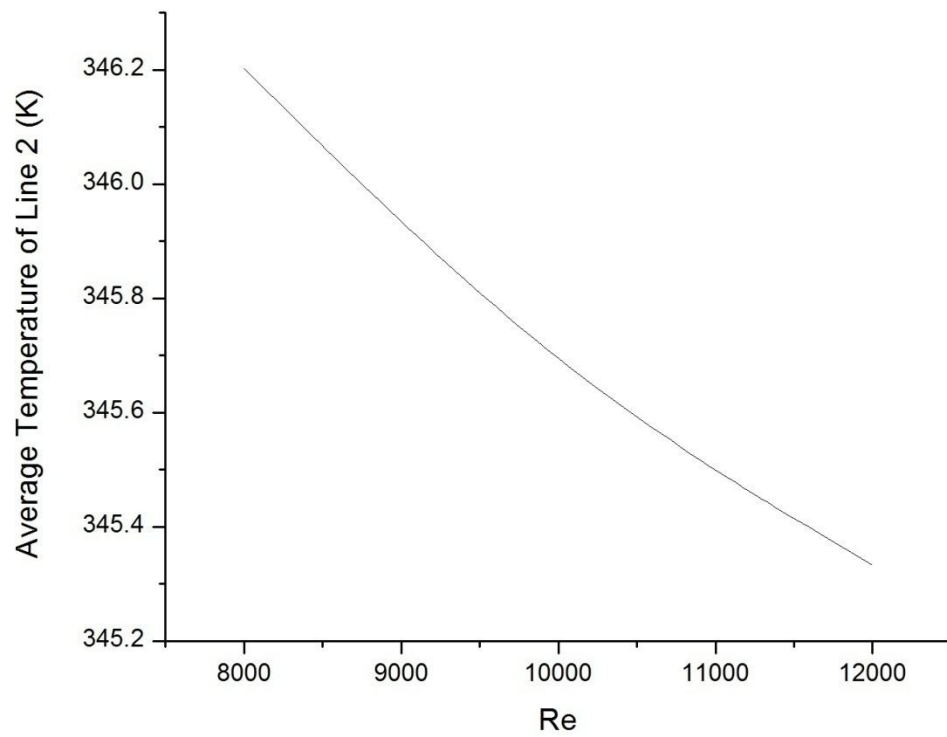


Table 5, Analysis of variance for the linear fit in figure 27

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	253.92213	253.92213	3.81E+08	3.26E-05
Error	1	6.67E-07	6.67E-07		
Total	2	253.92213			

Fig 28, Average temperature of line 2 vs. Re



2) Computer unit 3.

The average temperature of the vertical middle plane (line 3) was studied for computer unit 3. The average temperature of line 3 for all cases is 341.495K . Computer unit 3 ranked No.5 (from lowest average temperature to highest average temperature) for air-cooling performance.

The linear relationship between the average temperature of line 3 and inlet temperature is perfect. The equation obtained from a curve fit is:

$$T_{line\ 3} = 0.48069T_{inlet} + 203.62085$$

The adjusted R^2 value of this equation is very close to 1, and P value is much smaller than 0.05, this is a perfect linear fitting.

This equation shows that, the average temperature of line 3 decreases 0.481 degree when the inlet temperature decreases 1 degree.

The linear relationship between the average temperature of line 3 and computer unit heat output (Q) is also good. The equation obtained from a curve fit is:

$$T_{line\ 3} = 0.06115Q + 297.9356$$

For this equation, adjusted R^2 equals 1 and P-value equals 7.21×10^{-5} which is much smaller than 0.05, this proves this linear equation is excellent.

The linear fit tells that, for every 1000 W/m³ the heat output of computer unit 3 increases, the average temperature of line 3 will be increased 61.15 degrees.

The inlet velocity will not help cooling computer unit 3. In fact, the average temperature of line 3 increases when inlet velocity increases.

Fig 29, positions of computer unit 3 and line 3



Fig 30, Average temperature of line 3 vs. inlet temperature

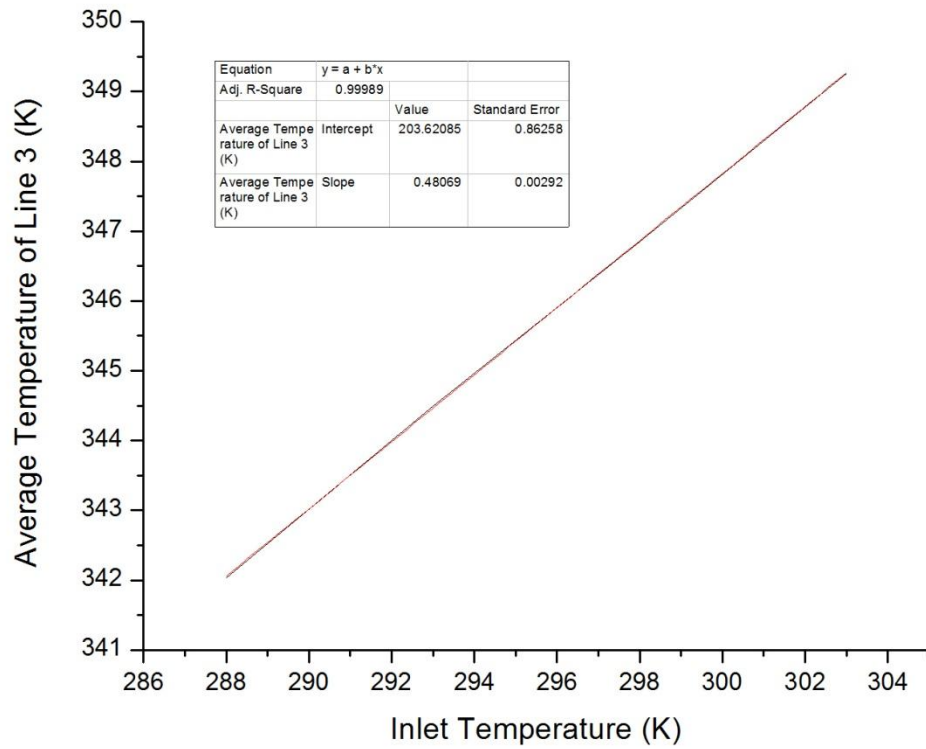


Table 6, Analysis of variance for linear fit in figure 30

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	28.88262	28.88262	27126.9367	3.69E-05
Error	2	0.00213	0.00106		
Total	3	28.88475			

Fig 31, Average temperature of line 3 vs. Q

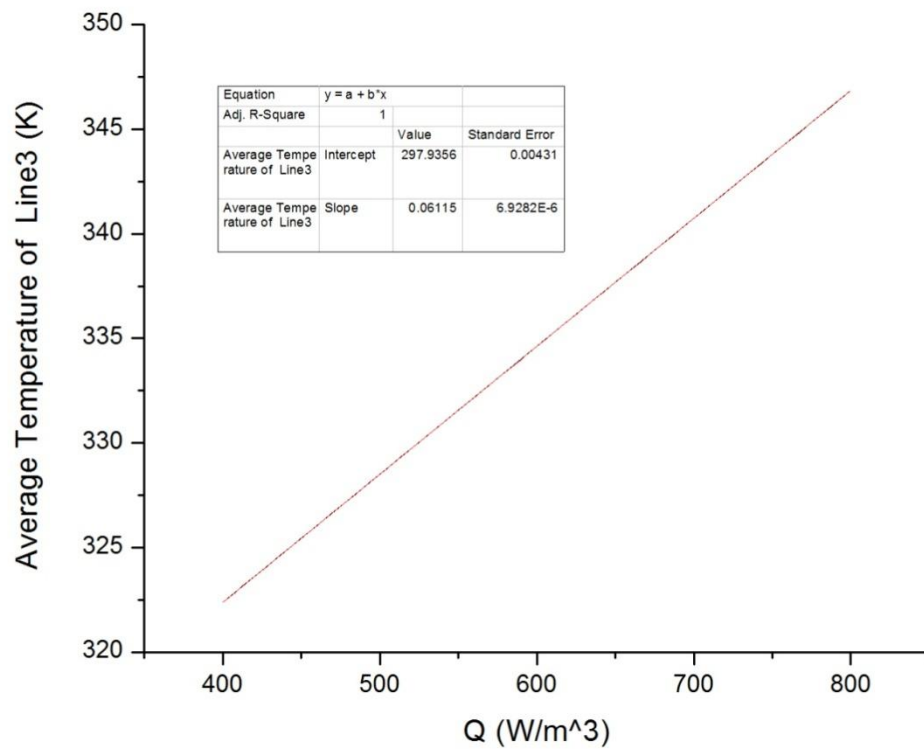
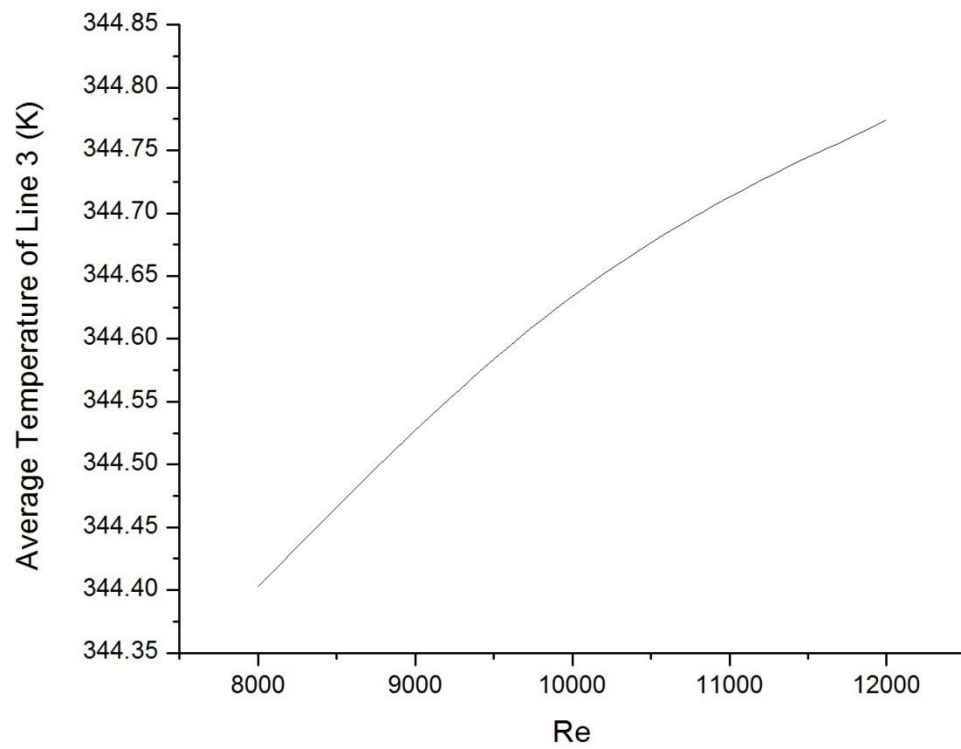


Table 7, Variance analysis for linear fit in figure 31

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	299.10667	299.10667	7.79E+07	7.21E-05
Error	1	3.84E-06	3.84E-06		
Total	2	299.10667			

Fig 32, Average temperature of line 3 vs. Re



4) Computer unit 4.

The average temperature of the vertical middle plane (line 4) was studied for computer unit 4. The average temperature of line 4 for all cases is 339.606K. Computer unit 4 ranked No.2 (from lowest average temperature to highest average temperature) in air-cooling performance.

The inlet temperature and average temperature of line 4 forms a perfect linear relationship. The equation obtained from a curve fit is:

$$T_{line\ 4} = 0.491T_{inlet} + 178.70308$$

The adjusted R^2 value for this linear fit is 1 and P equals to 1.64×10^{-7} , which proves this is a excellent linear equation.

This equations tells that, every 1 degree the inlet temperature lowered, the average temperature of line 4 will decrease 0.491 degree.

computer unit heat output (Q) and the average temperature of line 4 also forms a good linear relationship. The equation obtained from a curve fit is:

$$T_{line\ 4} = 0.05886Q + 297.9278$$

For this linear equation, adjusted R^2 is very close to 1 and P value equals to 9.37×10^{-5} This proves the linear fit is perfect.

From this linear fit, it is easy to tell that, the average temperature of line 4 will increase 58.86 degrees, while the heat output of computer unit increases 1000W/m^3 .

From figure 36, it is clear that increasing the inlet velocity helps cooling computer unit 4, but when Re equals 10000 or up, it will not influence the average temperature of line 4 significantly.

Fig 33, Positions of computer unit 4 and line 4



Fig 34, Average temperature of line 4 vs. inlet temperature

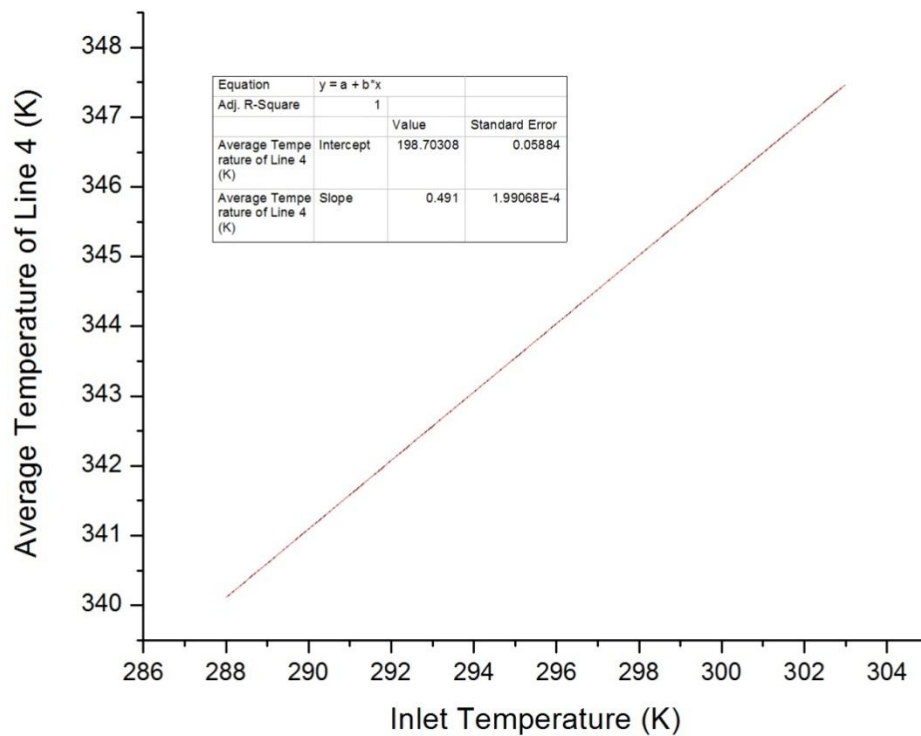


Table 8, Variance analysis for linear fit in figure 34

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	30.13537	30.13537	6.08E+06	1.64E-07
Error	2	9.91E-06	4.95E-06		
Total	3	30.13538			

Fig 35, Average temperature of line 4 vs. Q

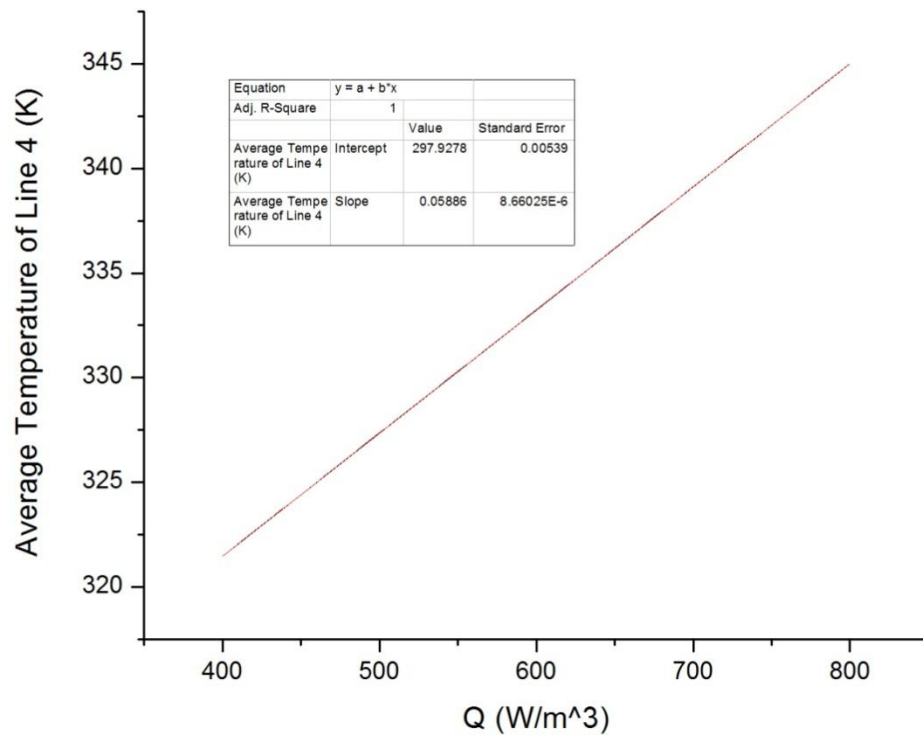
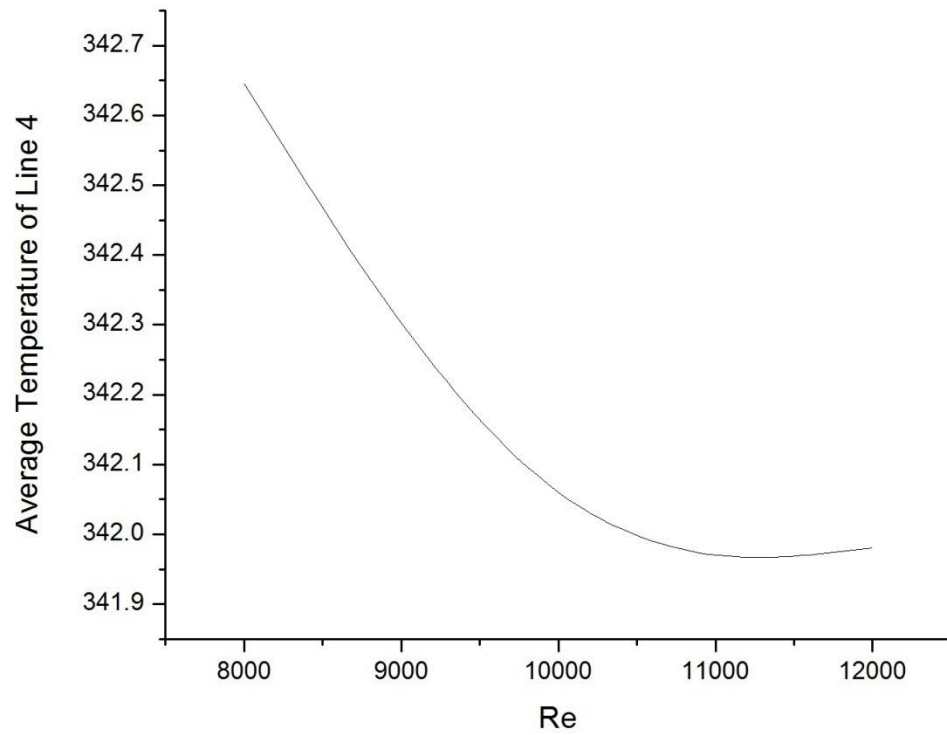


Table 9, Variance analysis for linear fit in figure 35

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	277.20706	277.20706	4.62E+07	9.37E-05
Error	1	6.00E-06	6.00E-06		
Total	2	277.20706			

Fig 36, Average temperature of line 4 vs. Re



5) Computer unit 5.

The average temperature of the vertical middle plane (line 5) was studied for computer unit 5. The average temperature of line 5 for all cases is 336.518K . Computer unit 5 ranked No.1 (from lowest average temperature to highest average temperature) for air-cooling performance.

As usual, the average temperature of line 5 forms a perfect linear relationship with inlet temperature. The equation obtained from a curve fit is:

$$T_{line\ 5} = 0.50677T_{inlet} + 190.63767$$

The adjusted R^2 value of this equation is almost 1. The P value of this linear fit is much smaller than 0.05. This proves this linear fit is very good.

This equation shows that average temperature of line 5 will decrease 0.507 degrees while the inlet temperature is lowered by 1 degree.

The linear relationship between computer unit heat output (Q) and inlet temperature is also perfect. The equation obtained from a curve fit is:

$$T_{line\ 5} = 0.05462Q + 297.9583$$

For this linear equation, adjusted R^2 is close to 1 and P value equals to 6.06×10^{-5} . This proves the equation is excellent.

This linear fit tells that, for every 1000W/m³ the heat output of computer unit 5 increases, the average temperature of line 5 will increase 54.6 degrees.

There is a good linear relationship between inlet velocity and the average temperature of line 5. The average temperature of line 5 decreases while the inlet velocity increases. Increasing inlet velocity will help cooling computer unit 5.

Fig 37, Positions of computer unit 5 and line 5

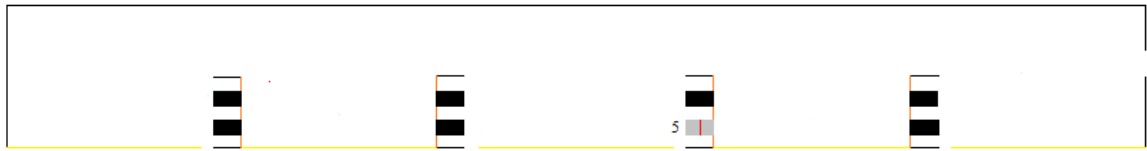


Fig 38, Average temperature of line 5 vs. inlet temperature

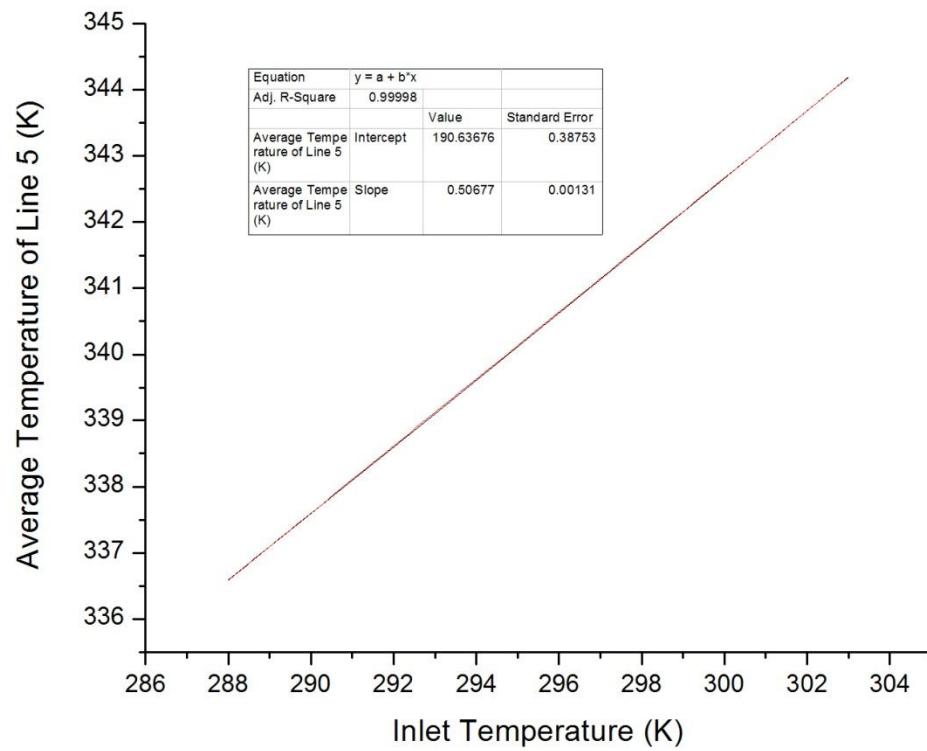


Table 10, Variance analysis for the linear fit in figure 33

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	32.10249	32.10249	149375.4	6.69E-06
Error	2	4.30E-04	2.15E-04		
Total	3	32.10292			

Fig 39, Average Temperature of line 5 vs. Q

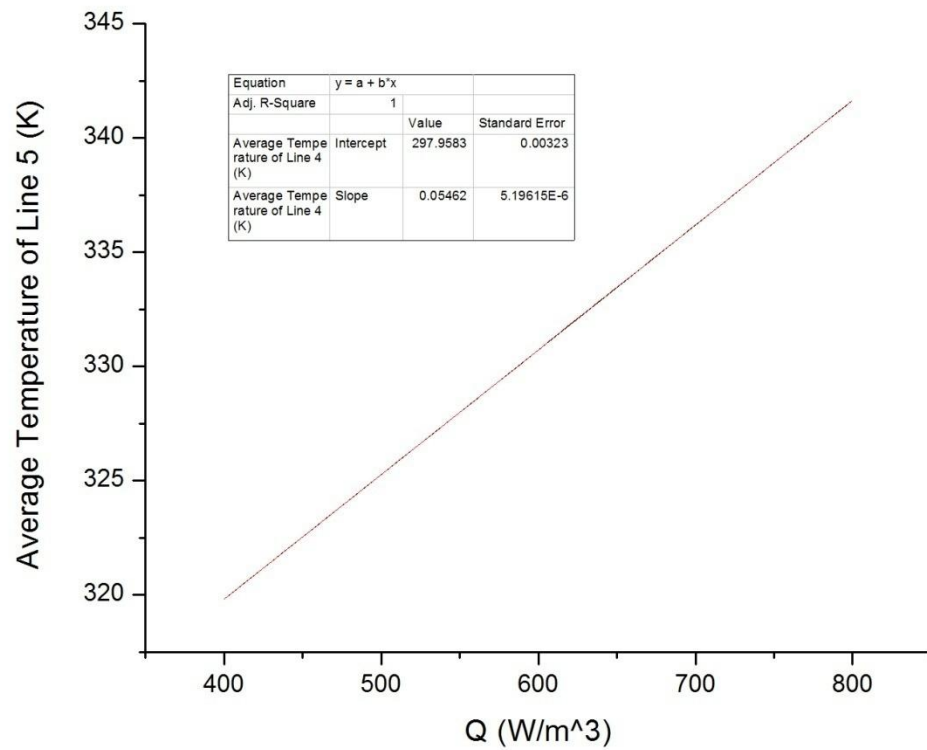


Table 11, Variance analysis for linear fit in figure 39

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	238.6326	238.6326	1.10E+08	6.06E-05
Error	1	2.16E-06	2.16E-06		
Total	2	238.6326			

Fig 40, Average temperature of line 5 vs. Re

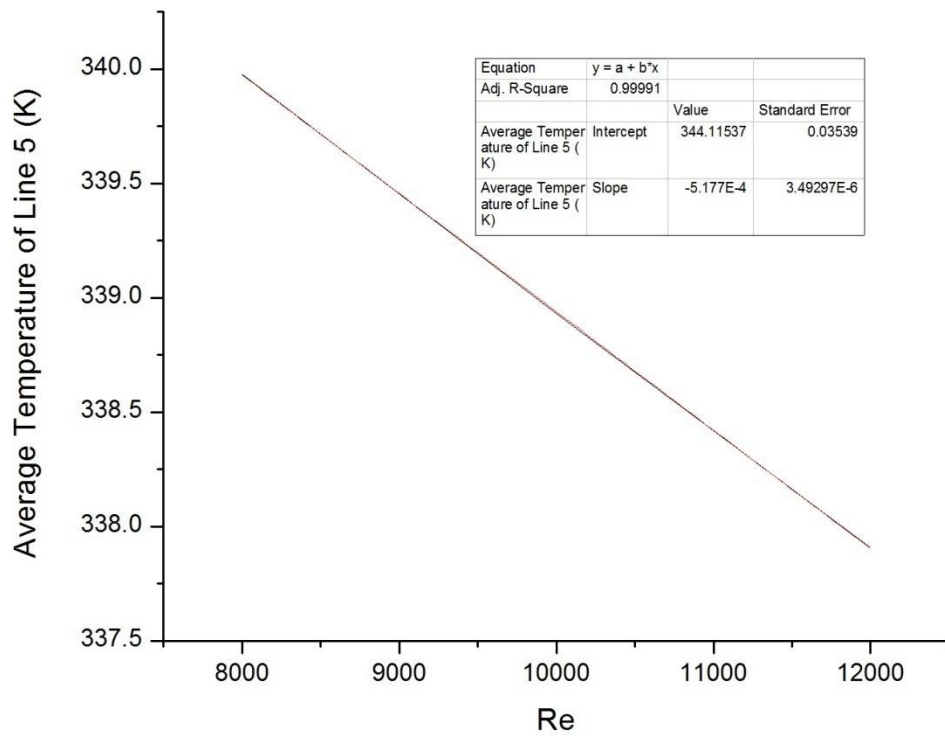


Table 12, Variance analysis for linear fit in fig 40

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	2.14411	2.14411	21966.80199	0.0043
Error	1	9.76E-05	9.76E-05		
Total	2	2.1442			

6) Computer unit 6.

For computer unit 6, the average temperature of the vertical middle plane (line 6) was studied. The average temperature of line 6 for all cases is 340.503K . Computer unit 6 ranked No.4 (from lowest average temperature to highest average temperature) for air-cooling performance.

The average temperature of line 6 and inlet temperature forms a good linear relationship. The equation obtained from a curve fit is:

$$T_{line\ 6} = 0.52415T_{inlet} + 189.98047$$

The adjusted R^2 value of this equation is almost 1 and the P value is much smaller than 0.05. This is a excellent linear fit.

This linear fit tells that, when inlet temperature is lowered by 1 degree, the average temperature of line 6 will decrease 0.524 degree.

The linear relationship between the average temperature of line 6 and computer unit output (Q) is also reasonable. The equation obtained from a curve fit is:

$$T_{line\ 6} = 0.06027Q + 297.96065$$

For this equation, adjusted R^2 equals to 1 and P value equals to 5.03×10^{-5} . These prove this linear fit is excellent.

For this equation, it is concluded that, for every 1000W/m³ the heat output of computer unit 6 increases, the average temperature of line 6 will increase 60.27 degrees.

The average temperature of line 6 decreases when inlet velocity increases. Increasing inlet velocity will help cooling computer unit 6.

Fig 41, Positions of computer unit 6 and line 6

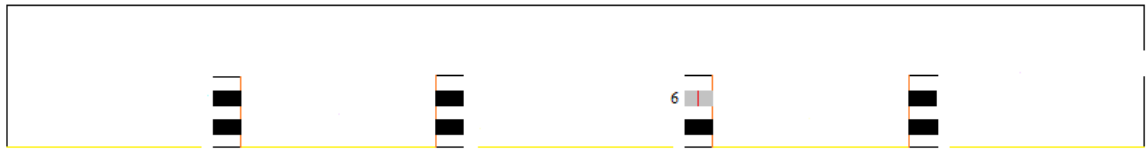


Fig 42, Average temperature of line 6 vs. inlet temperature

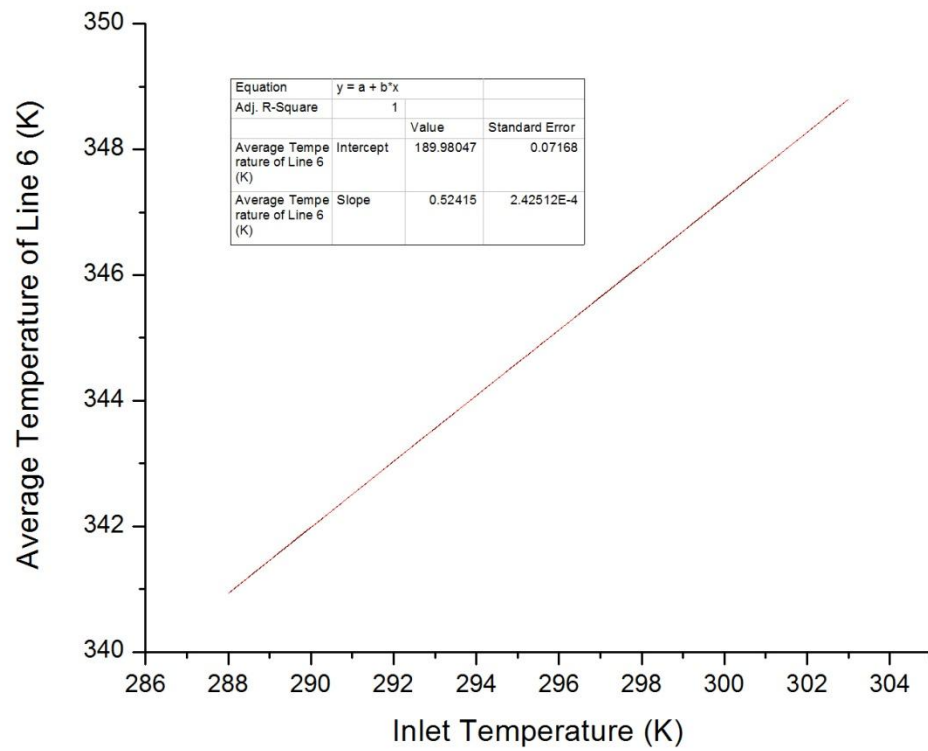


Table 13, Variance analysis of the linear fit in figure 42

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	34.34218	34.34218	4.67E+06	2.14E-07
Error	2	1.47E-05	7.35E-06		
Total	3	34.34219			

Fig 43, Average temperature of line 6 vs. Q

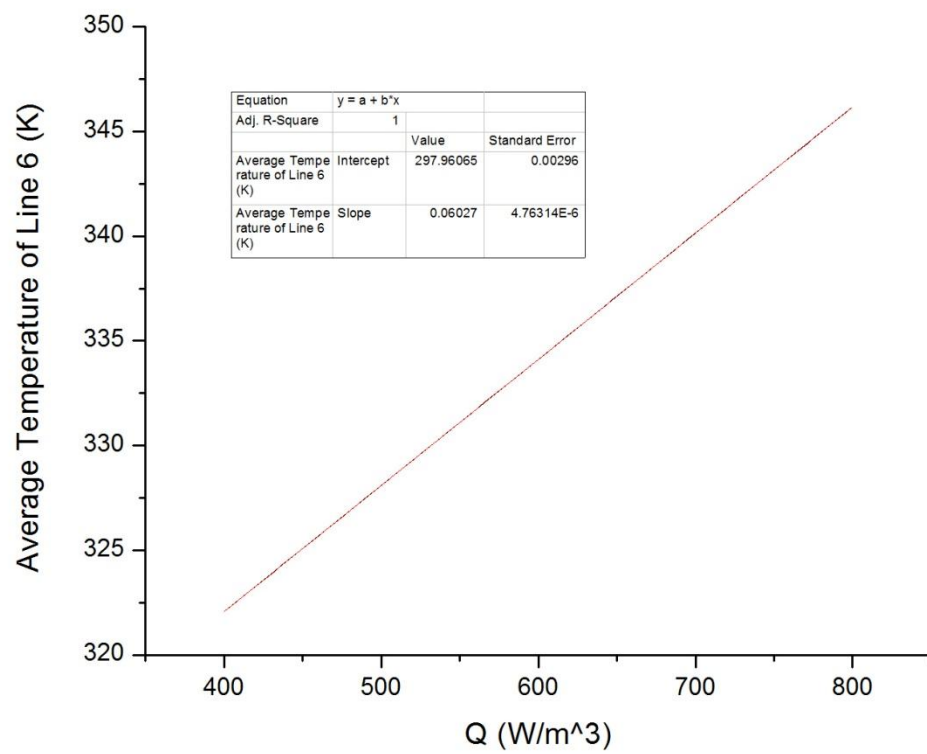
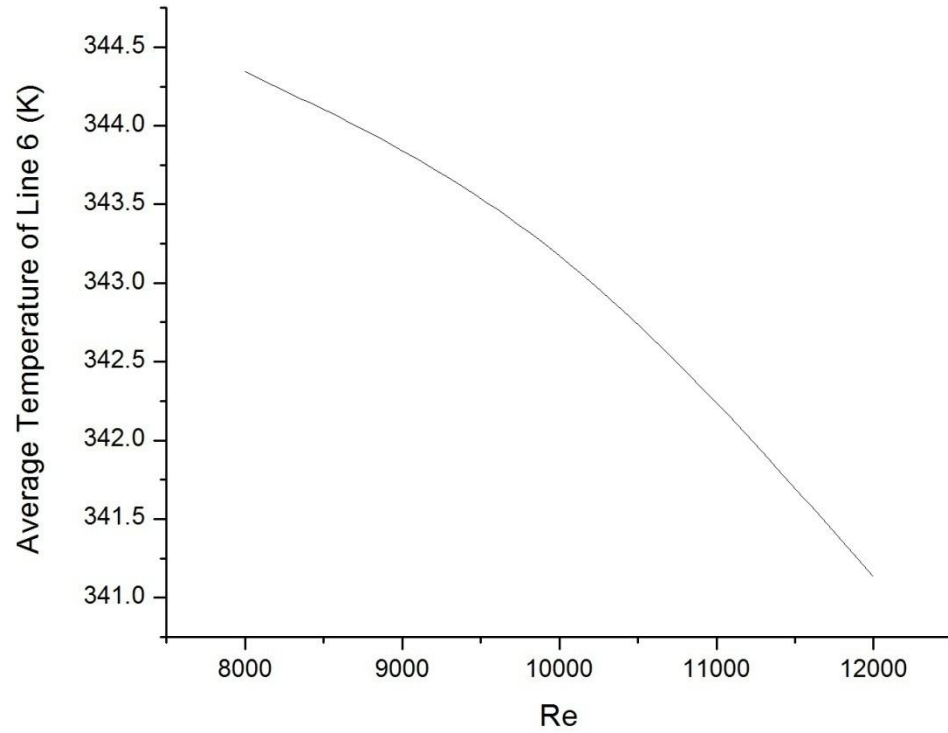


Table 14, Variance analysis of the linear fit in figure 43

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	290.5906	290.5906	1.60E+08	5.03E-05
Error	1	1.82E-06	1.82E-06		
Total	2	290.5906			

Fig 44, Average temperature of line 6 vs. Re



7) Computer unit 7

The average temperature of the vertical middle plane (line 7) was studied. The average temperature of line 7 for all cases is 356.757K . Computer unit 7 ranked No.8 (from lowest average temperature to highest average temperature) for air-cooling performance.

The average temperature of line 7 forms a excellent linear relationship with inlet temperature. The equation obtained from a curve fit is:

$$T_{line\ 7} = 0.48684T_{inlet} + 215.63151$$

The adjusted R^2 value of this linear fit is almost 1 and the P value of this linear fitting is very close to 0 which is much smaller than 0.05. These prove the linear fit is flawless.

This linear equation shows that, the average temperature of line 7 will be lowered by 0.487 degree when inlet temperature decreases 1 degree.

The computer unit heat output (Q) and the average temperature of line 7 also forms a perfect linear fit. The equation obtained from a curve fit is:

$$T_{line\ 7} = 0.07864Q + 297.94495$$

This linear fit has a P value of 9.49×10^{-5} which is much smaller than 0.05 and the adjusted R^2 value of this linear equation is 1. This proves it is an excellent linear equation.

This linear fit tells that, for every 1000W/m³ the heat output of computer unit 7 increases, the average temperature of line 7 will increase 78.6 degrees.

Increasing inlet velocity will actually increase the average temperature of line 7.
It will not help cooling computer unit 7.

Fig 45, Positions of computer unit 7 and line 7



Fig 46, Average temperature of line 7 vs. inlet temperature

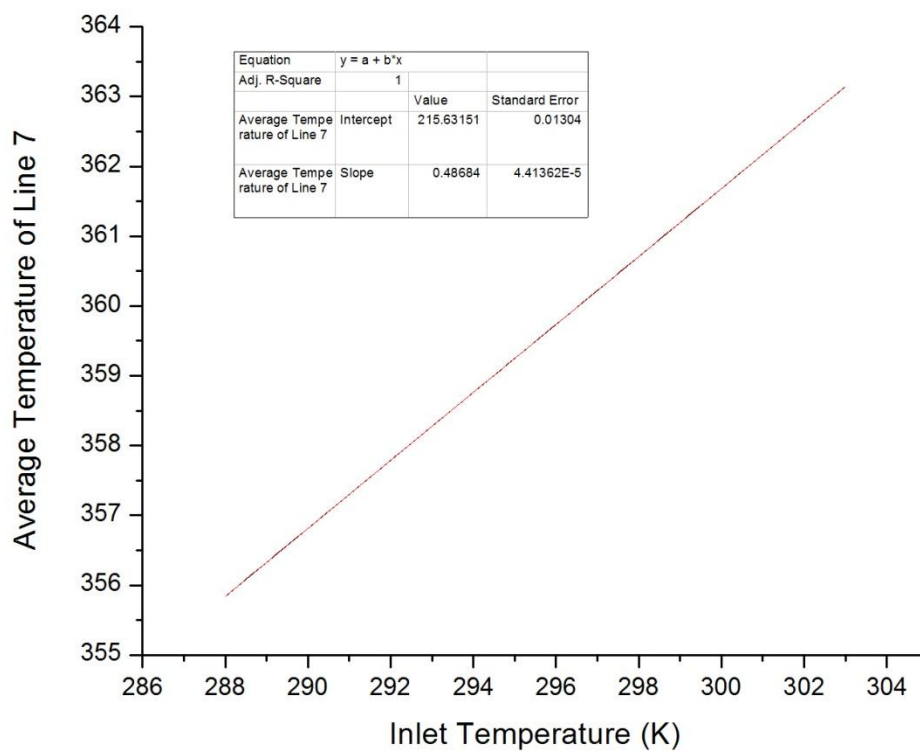


Table 15, Variance of the linear fit in figure 46

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	29.62689	29.62689	1.22E+08	8.22E-09
Error	2	4.87E-07	2.44E-07		
Total	3	29.62689			

Fig 47, Average temperature of line7 vs. Q

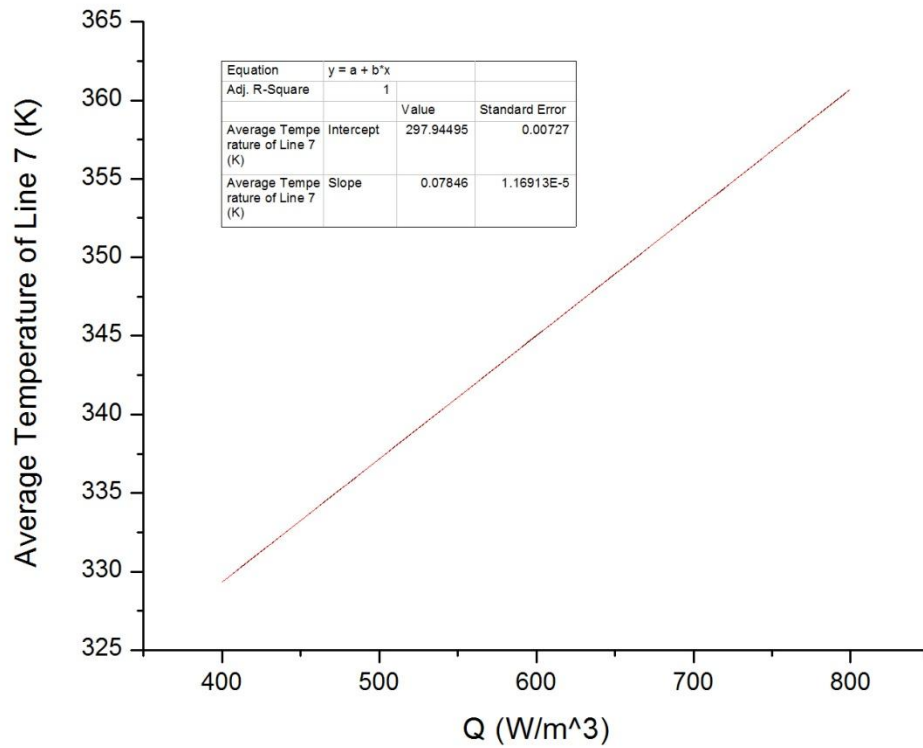
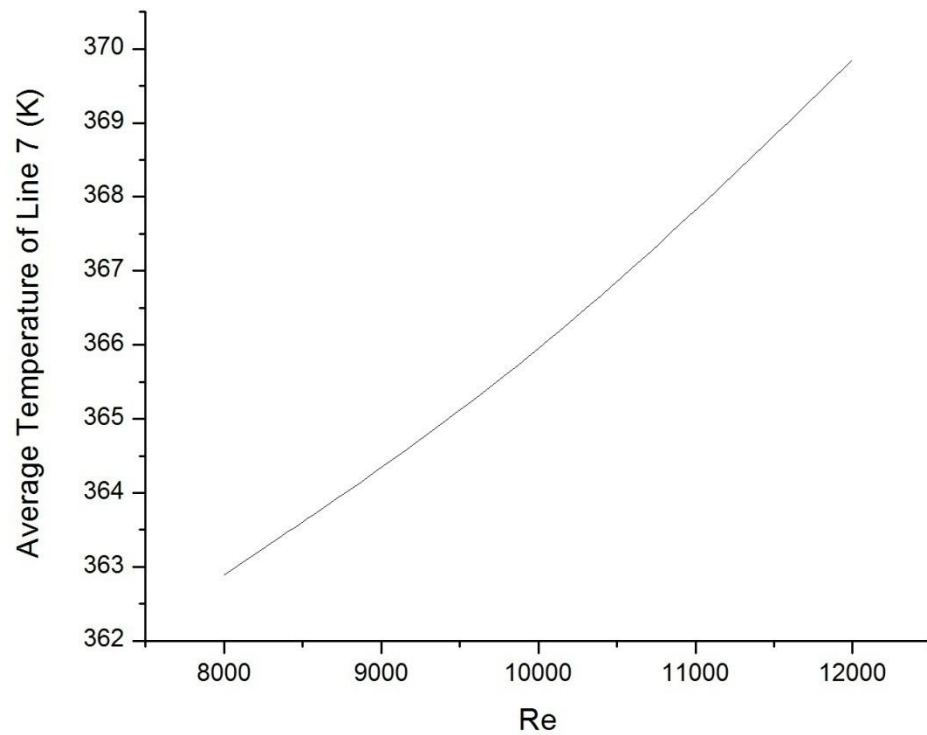


Table 16, Variance analysis for the linear fit n figure 47

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	492.45576	492.45576	4.50E+07	9.49E-05
Error	1	1.09E-05	1.09E-05		
Total	2	492.45577			

Fig 48, Average temperature of line7 vs. Re



8) Computer unit 8

The vertical middle plane of unit 8 (line 8) was studied. The average temperature of line 8 for all cases is 344.568K . Computer unit 7 ranked No.8 (from lowest average temperature to highest average temperature) for air-cooling performance.

The linear relationship between average temperature of line 8 and inlet temperature is perfect. The equation obtained from a curve fit is:

$$T_{line\ 8} = 0.49748T_{inlet} + 201.06873$$

This equation has an adjusted R^2 value of 1 which is excellent and the P value of this linear fit equals to 5.7×10^{-8} which is really small. These prove this linear equation is perfect.

This linear fit tells that when the inlet temperature decreases 1 degree, the average temperature of line 8 will decrease 0.497 degree.

The linear relationship between the average temperature of line 8 and computer unit heat output (Q) is also excellent:

$$T_{line\ 8} = 0.0642Q + 297.96277$$

The adjusted R^2 value of this equation equals 1 and P value of this equation is much smaller than 0.05, so this equation describes the relationship between the average temperature of line 8 and computer unit heat output (Q) well.

This linear fit shows that when heat output of computer unit 8 increases 1000W/m³, the average temperature of line 8 will increase 64.2 degrees.

The inlet velocity of line 8 will not help cooling computer unit 8. The average temperature of line 8 increases while inlet velocity increases.

Fig 49, Positions of computer 8 and line 8

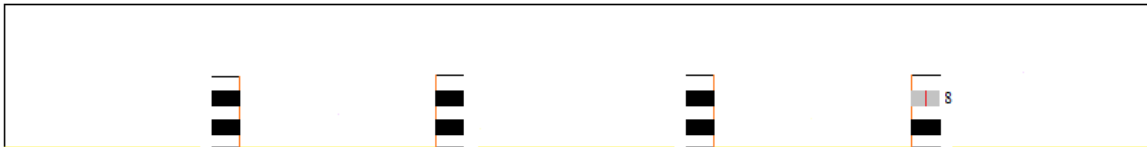


Fig 50, Average temperature of line 8 vs. inlet temperature

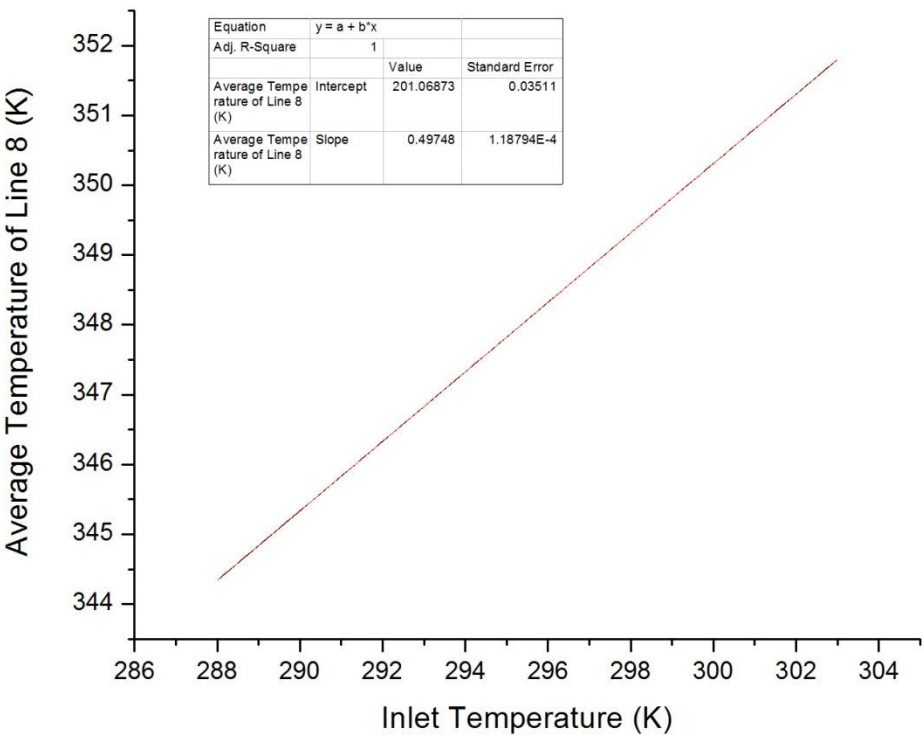


Table 17, Variance analysis of the linear fit in figure 50

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	30.93629	30.93629	1.75E+07	5.70E-08
Error	2	3.53E-06	1.76E-06		
Total	3	30.93629			

Fig 51, Average temperature of line 8 vs. Q

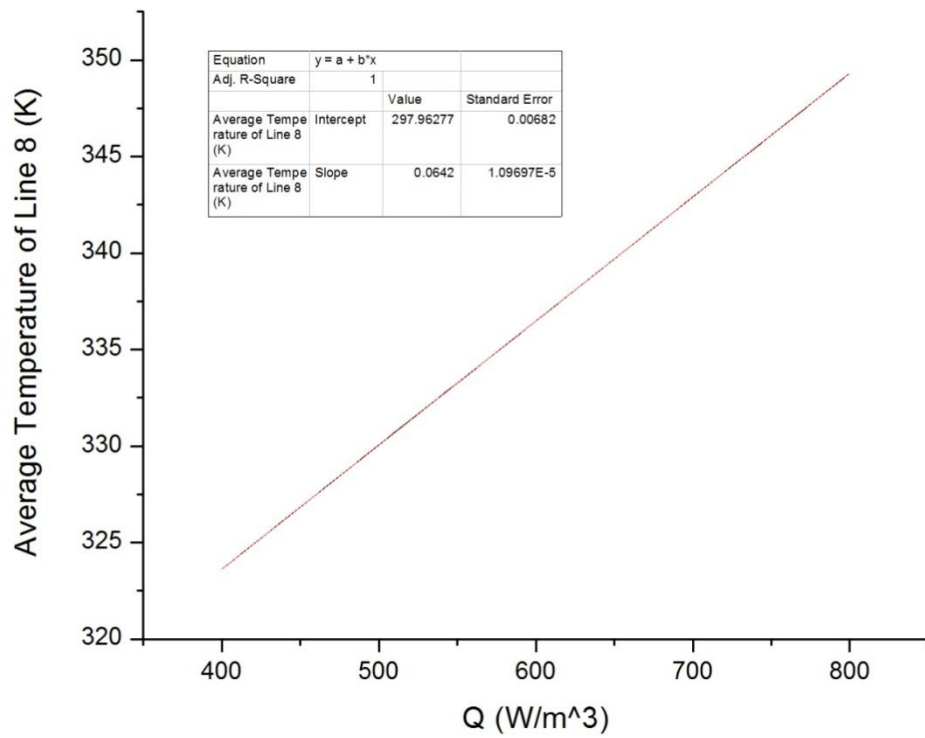
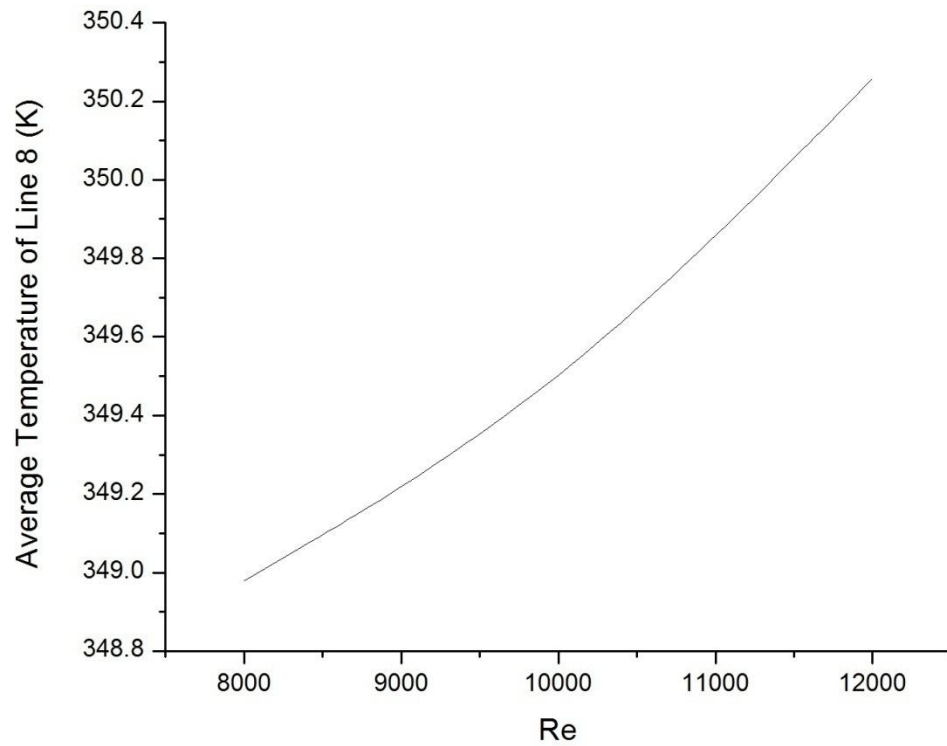


Table 18, Variance analysis of linear fit in figure 51

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	329.70038	329.70038	3.42E+07	1.09E-04
Error	1	9.63E-06	9.63E-06		
Total	2	329.70039			

Fig 52, Average temperature of line 8 vs. Re



For a macro view of how inlet temperature, computer unit heat output (Q) and inlet velocity (Re) influence the air cooling performance of the data center. The relationships between these facts and outlet temperature, maxima temperature were studied.

9) Outlet.

Average temperature of outlet forms a perfect relationship with inlet temperature. The equation obtained from a curve fit is:

$$T_{\text{outlet}} = 0.46916T_{\text{inlet}} + 166.26824$$

The adjusted R^2 value of this linear fit equals to 1. The P value of this linear fit is 7.9×10^{-8} which is much smaller than 0.05. These prove this linear fit can describe the relationship between inlet temperature and outlet temperature properly.

This equation shows, for every 1 degree the inlet temperature lowered, the outlet temperature will be lowered by 0.47 degree. This equation helps managing the outlet air flow when the inlet temperature changes.

The linear relationship between average outlet temperature and computer unit heat output is also excellent. The equation obtained from a curve fit is:

$$T_{\text{outlet}} = 0.01013Q + 297.96948$$

For this equation, adjusted R^2 equals 1 and P value is 3.9×10^{-4} . It is a flawless linear fit.

This equation tells that, for every $1000\text{W}/\text{m}^3$ the heat output of computer units increases, the outlet temperature will increase 10 degrees. This equation helps managing the outlet air flow when the heat output of computer units increase significantly.

Increasing the inlet velocity will decrease outlet temperature. It makes perfect sense since to carry out the same amount of energy from the data center, larger air flow will need less temperature drop.

Fig 53, Outlet Temperature vs. inlet temperature

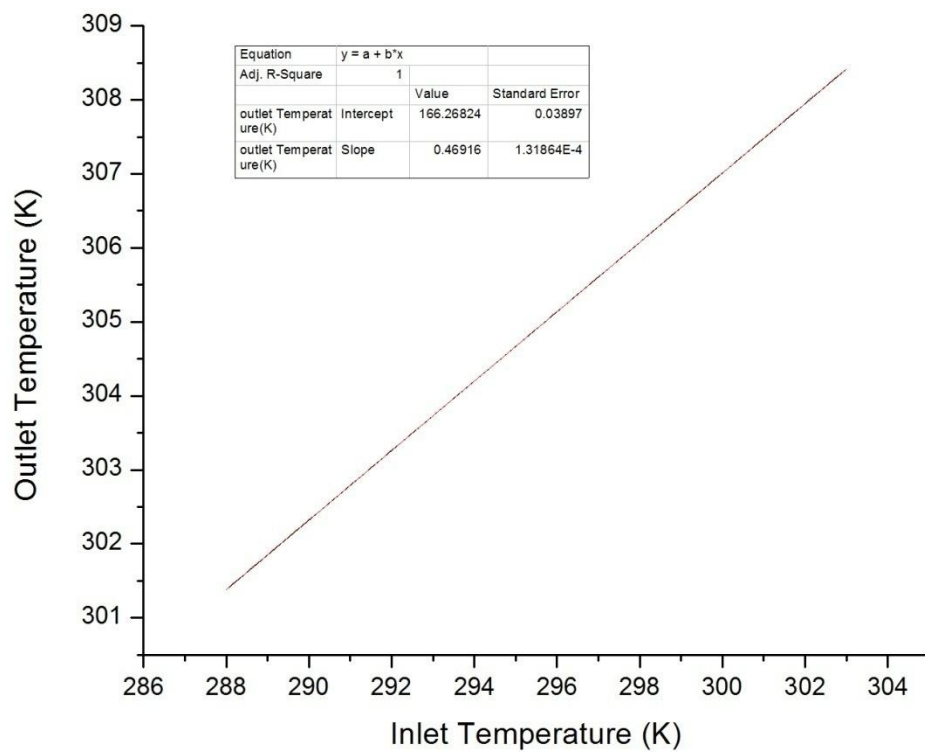


Table 19, Variance analysis for the linear fit in figure 53

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	27.51365	27.51365	1.27E+07	7.90E-08
Error	2	4.35E-06	2.17E-06		
Total	3	27.51366			

Fig 54, Outlet Temperature vs. Q

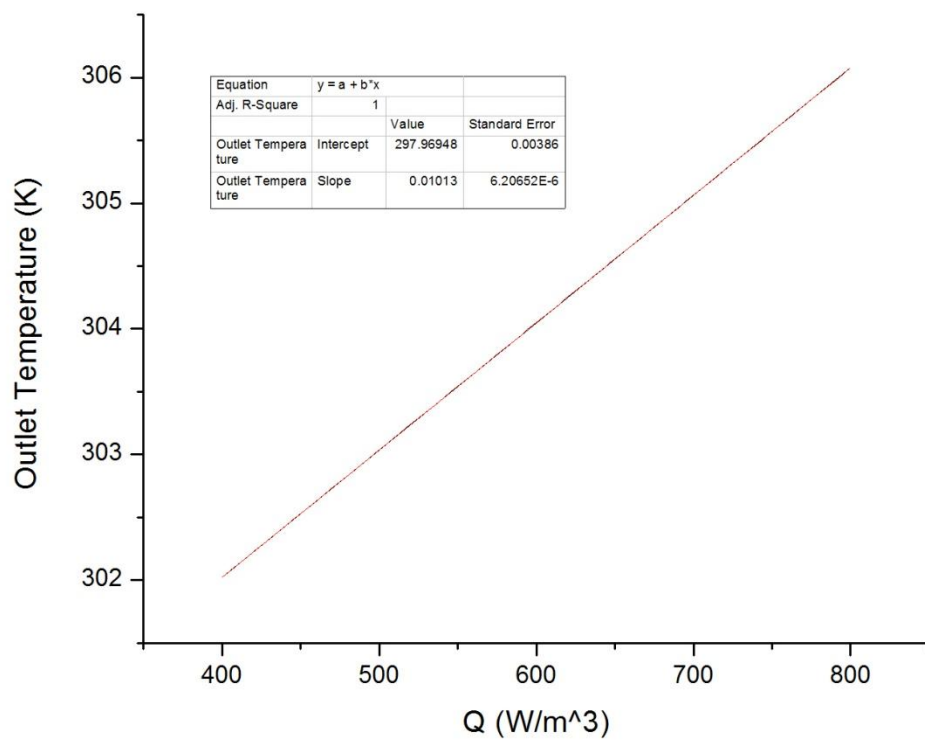


Table 20, Variance analysis of linear fit in figure 45

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	8.21624	8.21624	2.67E+06	3.90E-04
Error	1	3.08E-06	3.08E-06		
Total	2	8.21624			

Fig 55, Outlet Temperature vs. Re

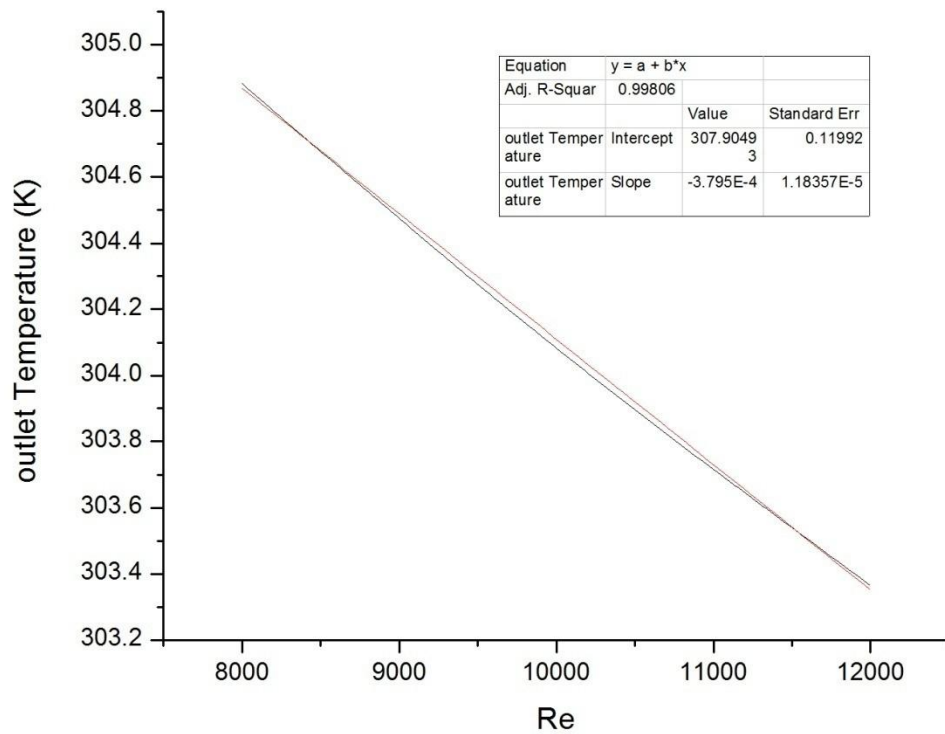


Table 21, Variance analysis of linear fit in figure 55

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	1.15216	1.15216	1028.1041	0.01985
Error	1	0.00112	0.00112		
Total	2	1.15328			

10) Maximum temperature.

In this study, maximum temperatures of the data center for all the cases take place at the center of computer unit 7.

The linear relationship between inlet temperature and maximum temperature of the data center is perfect. The equation obtained from a curve fit is:

$$T_{max} = 0.48686T_{inlet} + 216.21862$$

The adjusted R^2 value of this equation is very close to 1 and P value of this equation equals 5.06×10^{-9} which is much smaller than 0.05. This linear equation should describe the relationship between inlet temperature and maxima temperature of the data center properly.

This equation tells that if the inlet temperature decreases 1 degree, the maximum temperature of the data center will decrease 0.487 degree.

There is also a perfect linear relationship between the maximum temperature of the data center and computer unit heat output (Q). The equation obtained from a curve fit is:

$$T_{max} = 0.0792Q + 297.94433$$

For this equation, adjusted R^2 equals 1 and P value equals 9.28×10^{-5} . These prove this linear relationship is excellent.

This linear fit shows that maxima temperature of the data center will increase 79.2 degrees when the heat output of the computer units increases 1000W/m^3 .

Inlet velocity will not help lowering the maximum temperature of the data center.

Fig 56, Maximum Temperature vs. inlet Temperature

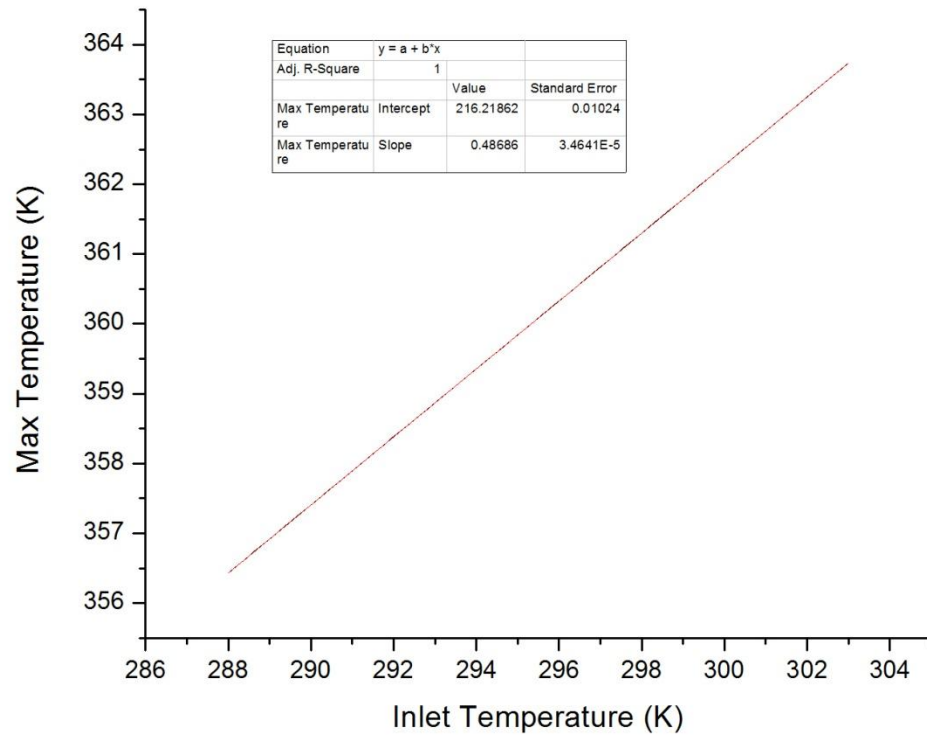


Table 22, Variance analysis for linear fit in figure 56

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	29.62908	29.62908	1.98E+08	5.06E-09
Error	2	3.00E-07	1.50E-07		
Total	3	29.62908			

Fig 57, Maximum Temperature vs. Q

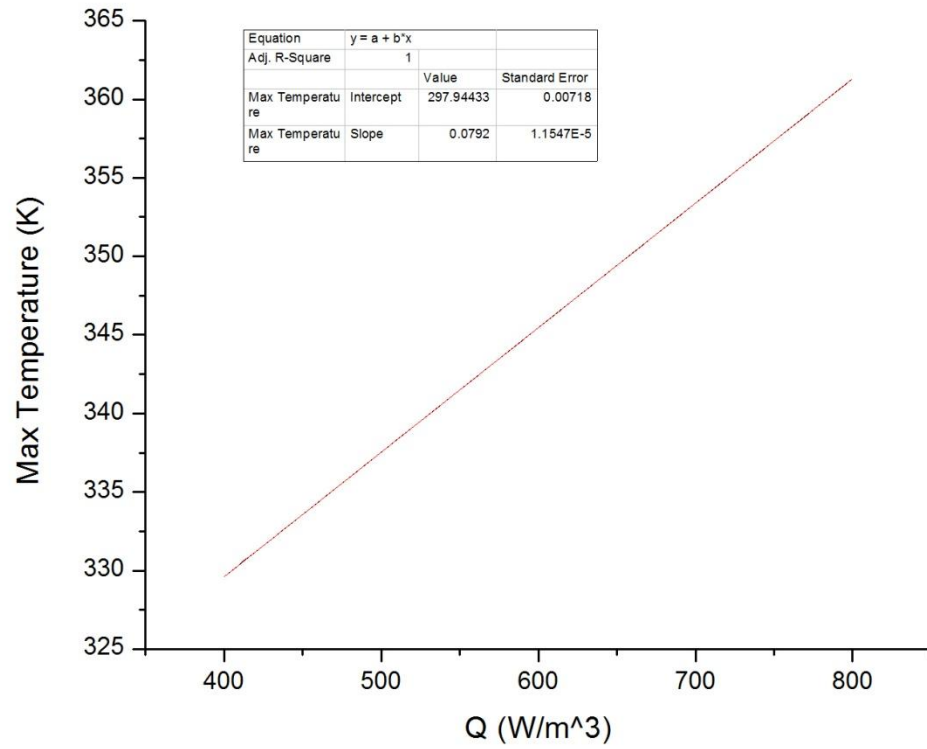
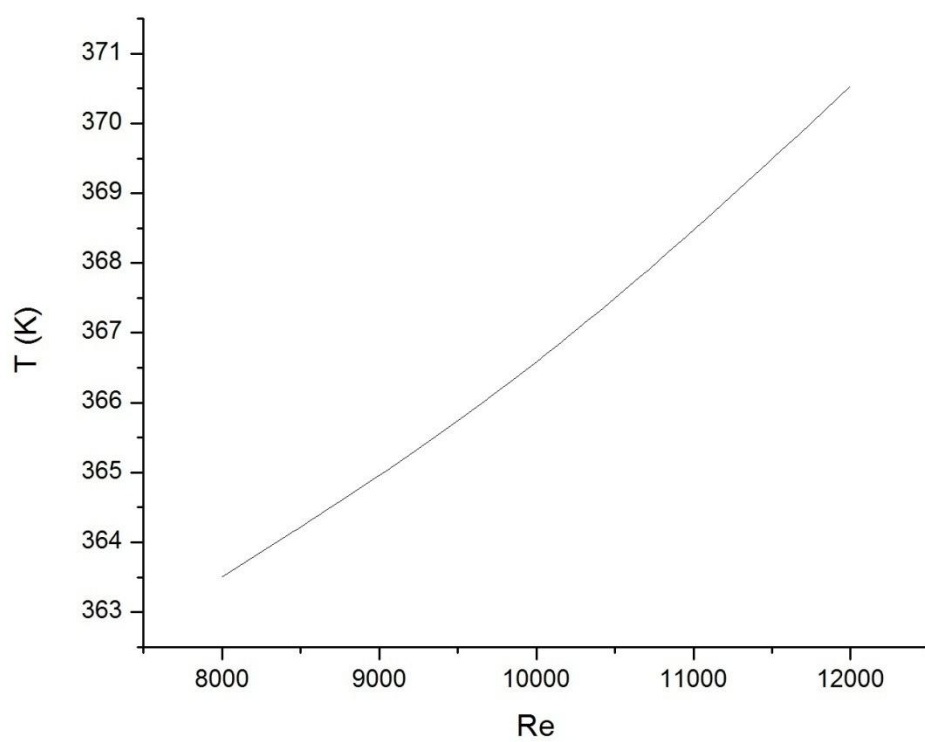


Table 23, Variance analysis for linear fit in figure 57

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	501.8112	501.8112	4.70E+07	9.28E-05
Error	1	1.07E-05	1.07E-05		
Total	2	501.81121			

Fig 58, Maximum Temperature vs. Re



VI, Conclusion.

It is concluded that the average temperatures of computer units are directly proportional to the inlet temperature. Although for each computer unit, the influence of the average temperature by inlet temperature varies, the average temperature of each computer unit will decrease at least 0.42 degree, when inlet temperature decreases 1 degree.

The maximum temperature of the data center decreases 0.487 degree when the inlet temperature decreases 1 degree. It seems controlling the inlet temperature is a good way to increase the performance of the air cooling system, but a major breakthrough should be achieved in the air-conditioner technology to let this option to be economically feasible, since every one degree the inlet temperature lowered by air-conditioner, 10 percent of more electric power may required [10]. Control the inlet temperature is a good way to maintain the temperature of the data center in a feasible range at normal cases, but in the conditions of emergency, it is certainly not good enough.

The average temperatures of computer units are also directly proportional to the computer unit heat output (Q). The average temperature of each computer unit will increase at least 54.62 degrees when the heat output of each computer unit increases 1000 W/m^3 .

In the research, it is found that the maximum temperature of the data center increases almost 80K every 1000 W/m^3 the Q increases. At present, it is common that the heat output of computer unit increases several thousand watts per cubic meter in emergency conditions, at that point, air cooling is just not enough to stop the heating

process. In fact, water-cooling system is indispensable in big data centers. It is very important to find a way to control the heat output of the computer unit, if this cannot be achieved, air-cooling do not stand a chance to solve emergency problems.

The position of the computer unit influence the overall air-cooling performance significantly. In this study, it is found that, inside of the same rack, computer unit which is in a higher position has a lower average temperature in most instances, and the average temperature of four computer units at a higher position is about 4 degrees lower than the average temperature of four computer units at a lower position. The reason for this phenomenon is maybe there is much more free space from the higher computer units to the top than the lower computer units to the bottom and the outlet of the data center is at a comparable higher position. The air pumped out by the fans near higher computer units has less trouble to reach the outlet and more free space around the computer units can absorb more heat. It tells us when building a data center, it is important to leave enough free space around the computer units, it maybe also a good idea to try to put the computer units at a position which is closer to the outlet vertically. It is found that, the average temperature of four computer units in the middle is 7 degrees lower than the average temperature of four computer units on the sides. Their distance from the outlet may cause this phenomenon. If the computer units are too far away from the outlet, it is harder for the hot air pumped out by their fans to reach the outlet, more hot air will be trapped in the area around the computer units, this will seriously influence the air cooling performance. When the computer units are too close to the outlet, the condition is even worse, the inlet cold air meets the hot air try to reach the outlet and forms a huge cyclone, this cyclone absorb the cold air enters the data center through the inlet closest to the

outlet, so much less cold air will go through the rack closest to the outlet (and in our study, the inlet of the rack which is closest to the outlet is on its right side, it may aggravate this phenomenon.), this will influence the air-cooling performance significantly. It is concluded that, do not put the computer units too close to the outlet horizontally and try to put computer units in the middle area of the data center.

The relationship between inlet velocity and average temperature of each computer unit is very complicated. It is clear that inlet velocity effect the average temperature of each computer unit but in different ways based on its position. The position of each computer unit influence the ability the hot air pumped out by their fans to reach the outlet. Increasing the inlet velocity will help the air-cooling performance of the computer unit, if the hot air pumped out by its fans can reach the outlet comparable more efficiently. In the study, it is found that increasing the inlet velocity will helps cooling the computer units at a higher position (except computer unit 8 since it is too close to the outlet) and helps cooling the computer unit in the middle area of the data center (except computer unit 4, because it is comparable far away from the outlet and it is at a lower position). It suggests that, for inlet velocity to play a role in air cooling performance, it is necessary to put the computer unit in a proper position.

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