ENERGY SAVING PERFORMANCE OF DISTRIBUTED HEATING AND COOLING SYSTEM FOR LABORATORY BUILDINGS

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ABSTRACT

An advanced distributed heating and cooling system utilizing small-scale high-performance heat pumps was designed to replace the central heating and cooling system for the AIST laboratory buildings, which have a total floor area of 36,100 m^2, of which 20,100 m^2 is occupied by laboratories. In the old system, the total primary energy required for hot water was 44 TJ and it was 12 TJ for chilled water, and 39 TJ of primary energy for heating and cooling purpose electricity was used in FY 2001. The new system is composed of small-sized high-performance heat pumps, with an average coefficient of performance (COP) of 3.1. The total energy consumption of the new system is estimated to be 61% of the old system, with a total energy saving of 37 TJ for one year. The total operating cost is estimated to be 63 %, and a savings of 44.7 million yen for one year. The total CO_2 emission is estimated to be 53%, a reduction of 2,400 tons of CO_2 per year. The improvement of the system is caused mainly by the high-performance small-scale heat pumps and the high-performance total system design that takes laboratory usage into consideration.

Key Words***: heat pumps, distributed energy systems, laboratory buildings, COP, CO_2 emission*****.**

1 INTRODUCTION

AIST Tsukuba is one of the research bases of the National Institute of Advanced Industrial Science and Technology (AIST) (AIST 2005). AIST Tsukuba is located in Tsukuba, Ibaraki prefecture, about 60 km northeast of Tokyo (Figure 1). A central heating and cooling system was installed in three of the AIST Tsukuba's four areas (i.e., East, West and Central, but not North). AIST Tsukuba has two Energy Centers for hot water and chilled water supply; one is for the West area and the other is for both East and Central areas (Figure 2). This central heating and cooling system is a district heating and cooling system. The facilities became obsolete after 24 years of operation after the predecessor laboratories of AIST Tsukuba moved to Tsukuba in 1980. Then, work began in 2003 on converting the central heating and cooling system for the East and Central area laboratory buildings into a distributed heating and cooling system. The reconstruction will be completed in 2005. The project was implemented after precise investigation of economic and environmental factors and includes the addition of electric power meters and calorie meters for measuring and improving the operation of the air-conditioners.

The climate of this district is similar to that of Tokyo. The location of Tsukuba is 140° east longitude, 36° north latitude and 25 m above sea level. The heating and cooling system requires cooling and heating as well as dehumidification. The average temperature is about 14°C and the average relative humidity is about 60%. Figure 3 shows the monthly atmospheric temperature of Tsukuba (JMA 2005). The data is the average of the last 3 years. Figure 4 shows the annual temperatures of Tsukuba, Tsuchiura and Tokyo. Tsuchiura borders on Tsukuba and has a greater amount of climate data available. The average temperature in each city shows a rising trend, with a 0.05°C increase per year in Tsukuba and Tsuchiura. The cooling requirement is thus becoming greater year by year.

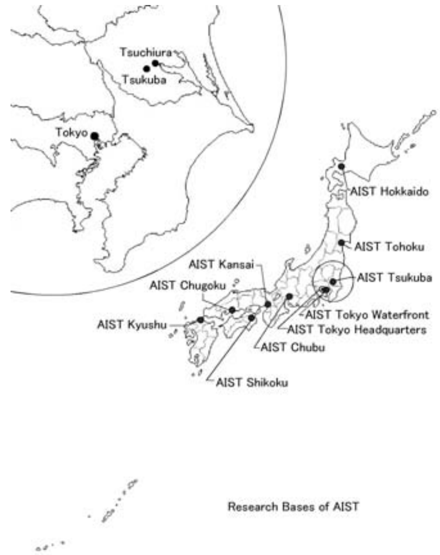

Fig. 1. AIST Tsukuba and its environs

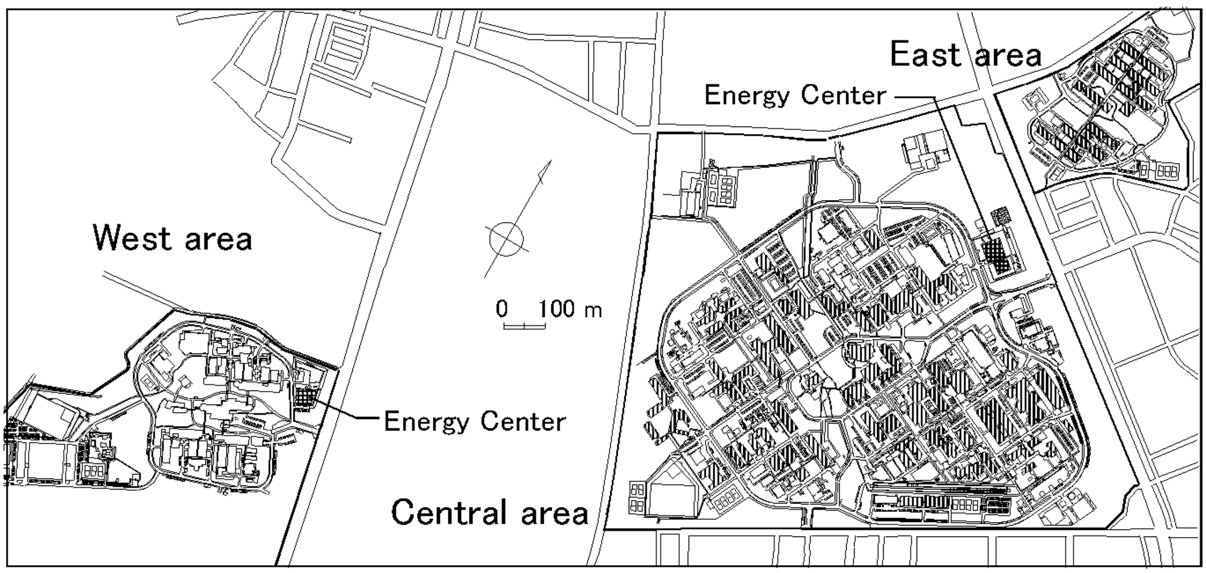

Fig. 2. West, East and Central area of AIST Tsukuba

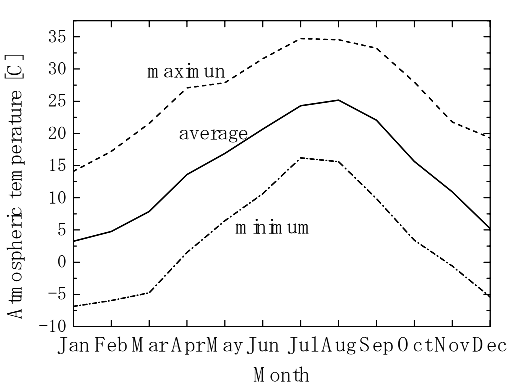

Fig. 3. Monthly temperatures at Tsukuba

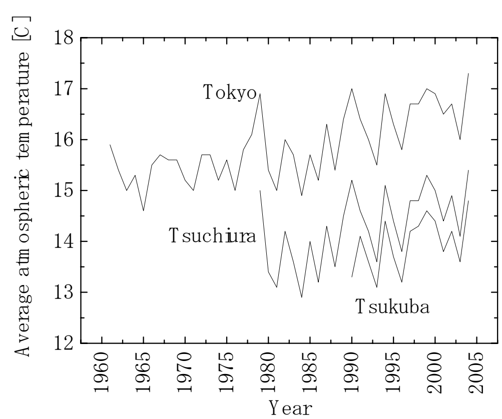

Fig. 4. Average temperatures at Tsukuba, Tsuchiura and Tokyo

2 SPECIFICATIONS OF OLD AND NEW HEATING AND COOLING SYSTEMS

2.1 Heating and Cooling Load

AIST Tsukuba East has a total floor area of 36,100 m^2, of which 20,100m^2 is used for laboratories and offices. Operations data show that Tsukuba East consumed 43.9 TJ for hot water and 12.1 TJ for chilled water and 7,600 MWh of electricity in FY 2001. Hot water is supplied to the air-handling unit of each building, at a temperature of 50–60°C in winter and chilled water is supplied at 6–7°C in summer. For moisture control purposes, hot water is supplied throughout the year. The heating and cooling system is divided into two types. Type I is for cooling, heating, and ventilation. When the old system was used for heating and cooling the rooms, an air-handling unit was installed in each room. For ventilation, new air was taken in from outside the building and cooled or heated for the space conditioning mode, and the humidity was adjusted before the air was supplied to each room and corridor. Here, the heating and cooling system is called Type I (a), and the ventilation system is called Type I (b). The second type (II) is for special space conditioning with precisely controlled temperature and humidity that is needed for some of the laboratory rooms. In the East area, chilled water from the Energy Center was used only for Type I ((a) and (b)) systems. The Type II system used water chillers to chill water.

2.2 Energy Center

The Energy Center centrally produces and supplies hot water and chilled water as heat energy sources as utility for research and heating and cooling of buildings at the institute and common facilities. These fluids are circulated through underground multipurpose conduit systems to be picked up by heat exchangers at the institute. The Energy Center also supplies drinking water and processed waste water (recycled water). The buildings highlighted by the hatched lines in Figure 2 were supplied with chilled water and hot water by the Energy Center in the Central area.

The Energy Center produces hot water using boilers that were also designed to supply steam for the turbines to drive the turbo chiller. So, to produce hot water, high-temperature steam is produced just once. Two kerosene-burning boilers produce 400°C and 3.92 MPa steam at the rate of 11,800 kg/hr, and one boiler produces steam at the same temperature and pressure at the rate of 21,300 kg/hr. Steam of this condition is used for the turbines to drive the turbo refrigerator and is also used to produce hot water at 2.06 MPa and 180°C. After its energy is released, the hot water returns to the Energy Center at 120°C. Figure 5 shows an outline of the water and steam paths.

Two turbo chillers produce 8.8 MW of chilled water each, and a larger turbo chiller produces 17.6 MW of chilled water. R22 is used as the refrigerant in both turbo chillers. The chilled water condition is 4°C for supply and 12°C for return. There are no clear specifications for efficiency, and only the boilers are required to have at least 90% efficiency. From the other specifications, the ratio of refrigeration to fuel combustion energy is estimated to be 0.802. The value is the total COP and is smaller than the COP of absorption machines. If the turbine efficiency is assumed to be 90%, the efficiency of the power generation by turbine is estimated to be 28.1%. The ratio of cooling capacity to estimated turbine shaft power 2.85, which is also the COP of the turbo chiller, and can be compared directly with the electric motor driven chiller. The value of 2.85 is rather small when compared to the most advanced turbo chiller, which operates with a cooling COP of more than 6.0.

Total energy efficiency of the Energy Center is 46%; this is the ratio of the total energy distributed to each building as hot water and chilled water to the total primary energy consumption of electricity and heat generation of the kerosene boilers.

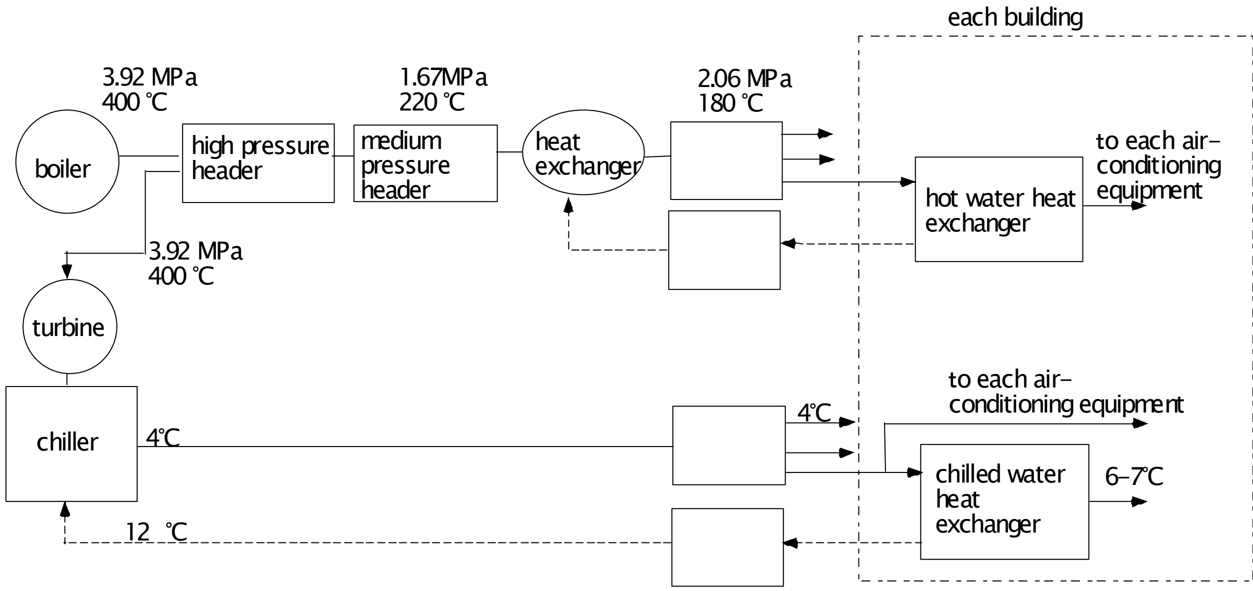

Fig. 5. Circuits of hot water and chilled water supplied by the Energy Center

There were several options for reconstructing the heating and cooling system: to continue the central heating and cooling system, to improve the efficiency of each facility or to introduce a co-generation system. Ultimately, the continuation of the central heating and cooling system by the Energy Center was abandoned, and it was decided to stop operation of the Energy Center at the end of FY 2004.

2.3 New Facilities and Apparatus

For Type I (a) and Type I (b) heating and cooling for the offices and ordinary laboratory rooms, and for ventilation, new heat pump (reversible air-air split heat pump) units were installed. The Type I (b) heating and cooling system includes electric heaters to compensate for the shortage of heating capacity for the cold air from outside and humidifiers in addition to the packaged units. Based on the results of contamination tests, the volume of fresh air intake was reduced by 55%.

For Type II, water chillers were installed to ensure heating and cooling with accurately controlled temperature and humidity. For the rooms where precise temperature and humidity control was not needed, double-bundle machines were installed. For the rooms where accurate control was needed, water chillers and natural-gas-fired boilers were installed. The one exception was a room that required humidity control at a low level and so a desiccant humidity control system was installed.

All new packaged heat pumps and water chillers use the new refrigerants, R407C and R410A. The COP of the newly installed chillers/heat pumps varies from 2.5 to 4.8, with the average being 3.1. The capacity of the selected packaged heat pumps for the Type I system is 1.6 times larger than the standard load of heating and cooling that is defined for the area for each machine.

Before reconstruction, there were also several packaged heat pump systems and chillers which operated independently of Energy Center. In those cases, there was no energy supply from Energy Center or there was no usage of energy from Energy Center. The number of packaged heat pump was 128 and that of chiller was 9 before the reconstruction. After reconstruction, the numbers changed to 652 and 6 respectively.

3 ENERGY CONSUMPTION PATTERNS AND ASSUMPTION OF ELECTRIC POWER

3.1 Energy Supplied from the Energy Center

Figure 6 shows the hot and chilled water energy received by the equipment in the East and Central areas. The left bar indicates hot water energy and the right bar (for summer months) shows the chilled water energy. The total height shows the energy supplied from the Energy Center, and the white part shows the energy loss from the pipes between the Energy Center and the main heat exchanger at each main building. The total energy supplied by Energy Center is 232,558 GJ, and the energy received by all buildings in East and Central buildings is 193,194GJ. And the energy received by East area building is 25,694 GJ. Hot water loss is 18% and chilled water loss is about 10% and the total loss is about 17%, throughout the year. Energy received at the East area is the lowest part of the bars.

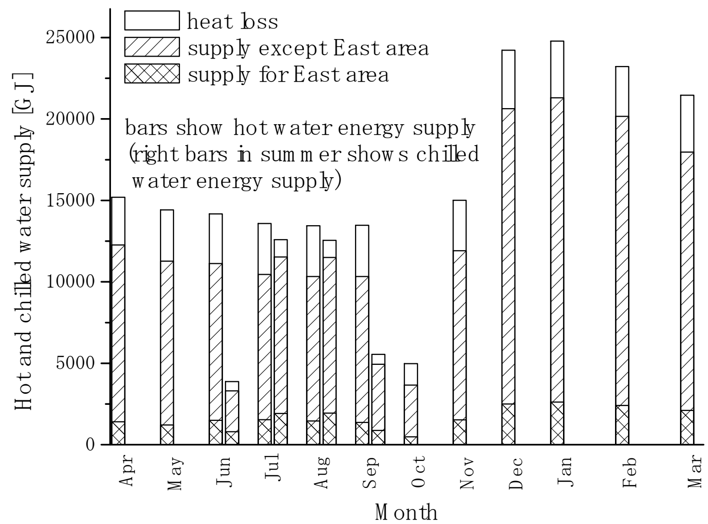

Figure 6 Hot and chilled water supply by Energy Center (FY2001)

One of the characteristics of the system is that there is high hot energy demand even in the summer, because Type II and Type I (b) systems require considerable energy for humidity control. The total capacity of the turbo chillers is mach higher than the demand, and there was not a case where all three turbo chillers were in operation at a time in 2001.

3.2 Assumption of Electric Power for Heating and Cooling

The energy supplied by Energy Center was measured for years. But the electric power for auxiliary equipments such as pumps and funs and the electric power for heat pumps, which were independent of Energy Center, were not measured. And a measurement of the electric power for new system is not completed yet. So the electricity consumption data on the auxiliary equipments and independent heat pumps of old system, and the all data of new system must be estimated.

Table 1 shows the sum of the rated electricity consumption of the equipment. In the new system, the electric power consumption rate of the newly-installed Type I heating and cooling system is about 1700 kW and that of the Type II special heating and cooling system is about 460kW. Including old facilities that are used, the total consumption increases by 75%, from 2000 kW to 3500 kW. However, the cooling capacity of new equipment for the Type I system is 162% of the cold energy used in FY 2001, and 62% can be considered as the margin.

Table 1. Comparison of rated electricity consumption (kW)

		before reconstruction	after reconstruction		
		old equipment	new equipment	Old equipment	total
Type I	summer	1,100.9	1,397.5	848.6	2,246.1
	winter	1,049.1	1,723.0	818.4	2,541.4
Type II	summer	971.2	461.9	573.3	1,035.2
	winter	971.2	461.9	573.3	1,035.2

The old equipment was not installed with power meters, so there is no data on the direct electric power consumption of the old system. To estimate the power consumption, two coefficients were introduced. One coefficient is C_l, the load factor of the heating and cooling facilities. This factor is the ratio of the biggest load to the capacity of the facilities. C_l of the Type I system was determined from the data for August, when the cooling load was the highest for the year. The Type II system uses hot water throughout the year, and it is difficult to separate the hot water usage into Types I and II. So this C_l is used commonly for the heating mode.

C_l of the Type II system was determined from the data for June, when this system accounts for almost all of the hot water usage. The capacity was estimated from the pump flow rate of the water at a constant temperature difference for the Type I system, and from the capacity of the heat exchangers, humidifier, and preheater and reheaters. C_l was determined by the following equation:

$$C_l = \frac{Q}{\sum q \times t} \tag{1}$$

where Q: energy supplied as chilled water or hot water at Tsukuba East (J)

for Type I system Q in August, for Type II system Q in June

q: chilled water or hot water consumption rate (J/h)

for Type I system, q =(rated flow rate of pump (L/h)) $\times$ (rated temperature difference of water (7 °C)) $\times$ (specific heat of water (J/kg/C) $\times$ (density of water (kg/L))

for Type II system, q = (rated heat consumption from hot water (J/h))

t: operation time of the month (h)

for Type I system t = 12 (hours/day) $\times$ 20 (days/month)

for Type II system t = 24 (hours/day) $\times$ 30 (days/month)

From these calculations, C_l values of 0.716 and 0.538 were obtained for the Type I and Type II systems, respectively.

The second coefficient is C_m, the ratio of the heating and cooling demand of each month to the highest demand, based on a published study (Ojima 1995). In that report, both the cooling and heating loads of an office building are presented for each month of the year, and this data is frequently used as the standard. Here, for the Type I system, the heating model pattern was applied for November to March, and the cooling pattern was applied for June to September. For the Type II system, the heating model pattern was applied for November to April, and the cooling pattern was applied for May to September. Thus, the electric power consumption data was arranged to be the same load pattern for both Type I and Type II of the old system. Table 2 shows the value of C_m, which is used commonly for both Type I and Type II of the new system.

Table 2. Electric power consumption ratio, C_m

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
cooling					0.327	0.673	0.926	1.000	0.809	0.377		
heating	1.000	0.984	0.790	0.306							0.202	0.702

Electric power consumption of each month, L (kWh), is estimated by the following equation.

$$L = P \times t \times C_l \times C_m \qquad (2)$$

where P : Total rated electric power consumption rate (kW)

t : operation time of the month (h)

For the new system, similar methods are applied. Table 3 shows the values calculated by the method above.

Table 3. Estimation of electric power consumption of each month (GWh)

	before reconstruction				after reconstruction							
	Type I		Type II		Type I				Type II			
	summer	winter	summer	winter	summer		winter		summer		winter	
					old	new	old	new	old	new	old	new
Jan		180.3		376.2			140.6	182.9			222.1	178.9
Feb		177.4		370.1			138.4	179.9			218.5	176.0
Mar		142.5		297.3			111.1	144.5			175.5	141.4
Apr		stop		115.3			43.1	56.0			68.1	54.8
May	stop		123.1		47.7	48.5			72.7	58.5		
Jun	127.3		253.1		98.1	99.8			149.4	120.4		
Jul	175.2		348.3		135.0	137.3			205.6	165.7		
Aug	189.2		376.2		145.8	148.3			222.1	178.9		
Sep	153.0		304.2		117.9	119.9			179.6	144.7		
Oct	stop		141.7		54.9	55.8			83.6	67.4		
Nov		36.3		75.8			28.4	36.9			44.8	36.1
Dec		126.5		263.9			98.7	128.3			155.8	125.5

3.3 Cost Calculation of Energy at the East Area Supplied from the Energy Center

Table 4 shows the running cost of the Energy Center and the East area's partial cost of energy from the Energy Center. In order to distribute the total cost to the East area, the value of 0.133 was used to express the ratio of the energy received by the East area to the total energy received by all buildings in the East and Central areas.

Table 4. Running cost of Energy Center and East area's share in FY2001

	Energy Center		East area's share	
	consumption	cost (yen)	consumption	cost (yen)
Electricity	10,036.6 MWh	170,379,000	1,334.8 MWh	22,659,688
Kerosene	9,015 kL	270,463,000	1,199 k L	35,970,438
Tap water	57,272 m^3	15,693,000	7,617 m^3	2,087,103
Processed water	178,851 m^3	49,005,000	23,786 m^3	6,517,458
	total	505,540,000	total	67,234,687

4 EVALUATION OF ENERGY SAVINGS AND ENVIRONMENT PROTECTION

4.1 Comparison of Energy Consumption

Table 5 compares energy consumed in the East area for heating and cooling. The left part of the table shows the energy consumed before reconstruction, mainly provided by the Energy Center, and the right part shows the energy consumption after the reconstruction, utilizing the distributed energy system in FY 2004. In the old system, electricity used for heating and cooling energy accounted for 57% of total energy consumption in the East area. The values show the primary energy. The new system, the distributed energy system, consumes 12,520 GJ more in primary energy than the old system for electricity and requires 6,140 GJ for the combustion of natural gas. However, stopping the energy supply from the Energy Center resulted in a reduction of 56,020 GJ of kerosene combustion. The total energy consumption will thus drop to 61%, representing an energy savings of 37,360 GJ.

Equation (2) was also used to estimate natural gas consumption of the new Type II system. Inserting the rated gas consumption into P, then L shows the natural gas consumption during the year. For the estimation of natural gas consumption, C_l was 0.538, and C_m was the same as that shown for the electricity consumption in Table 2.

Table 5. Primary energy consumption of East area (GJ)

	before reconstruction				after reconstruction			
	Type I		Type II		Type I		Type II	
Electricity	summer	winter	summer	winter	summer	winter	summer	winter
	5,801.3	5,966.4	13,919.6	13,488.7	10,883.5	11,599.5	14,836.4	14,377.2
Sub total	39,176.0				51,696.6			
Energy Center		hot water 43,916.3		chilled water 12,098.8		-		-
Natural gas	-		-		-			6136.4
Total	95,191.1				57,833.0			

* Electric power generation efficiency: 40%; kerosene calorific heat: 36.7MJ/L

Next, the factors of 37 TJ of saved energy were examined. As one of the factors of increase, the new Type I system was assumed to be in operation in April, May and October, while the old system Type I heating and cooling was stopped, increasing the energy consumption by 2.7 TJ. For the Type I (b) system, electric heaters were added to increase the humidity. The total capacity of the heaters is about 300 kW and accounts for 18% of the total rated electricity consumption of new Type I system in winter, for an increase of 0.2 TJ in energy consumption. Total increase in energy consumption was about 2.9 TJ.

The reduction of energy consumption derived from the removal of pumps, the introduction of small boilers, the reduction of fresh air intake and the effect of high COP heat pumps. The removal of water pumps for the Type I system, for which the total rated electric consumption was 109 kW, resulted in an energy savings of 1.2 TJ. New boilers for the Type II system are expected to have about 90% boiler efficiency because of the on-site usage, and are estimated to reduce energy consumption by 6.5 TJ. The reduction of intake air for ventilation to 45% of that of the old system, contributes to the reduction of energy required for energy for heating and cooling and also for operation of the blowers. The energy for temperature control is 4.2 TJ and the electric power for blowers is 180 MWh. So, this intake air reduces energy consumption by a total of 10.7 TJ. Finally, the contribution of the heat pumps can be determined so that the sum of the energy reduction and increase equals 37 TJ. Therefore, the value is set to 21.5 TJ. This corresponds to 23% of the total energy of the old system. The new heat pumps of which COP is 3.1 are expected to achieve the reduction in primary energy.

4.2 Comparison of Costs, CO_2 Emission and Air Pollutants

The same tendency is observed in Tables 6 and 7 for cost and CO_2 emission, respectively. A total of 44.7 million yen will be saved and CO_2 emission will be decreased by 2,370 t, which is a reduction of about 37% and 47% of the cost and CO_2 emission, respectively.

Table 6. Comparison of energy cost (yen)

	before reconstruction				after reconstruction			
	Type I		Type II		Type I		Type II	
Electricity	summer	winter	summer	winter	summer	winter	summer	winter
	7,799,553	8,021,454	18,714,061	18,134,855	14,632,246	15,594,893	19,946,699	19,329,343
Sub total	52,669,923				69,503,181			
Energy Center	electricity			22,659,688				
	kerosene			35,970,438				
	tap water			2,087,103	-		-	
	processed water			6,517,458				
	sub total			67,234,687				
Natural gas	-		-		-			5,597,175
Total	119,904,610				75,233,622			

* Electricity: 12.1 yen/kWh electricity; kerosene: 30yen/L; tap and processed water: 274yen/m^3; natural gas: 42yen/m^3

Table 7. Comparison of CO_2 emissions (t)

	before reconstruction				after reconstruction			
	Type I		Type II		Type I		Type II	
Electricity	summer	winter	summer	winter	summer	winter	summer	winter
	232.1	238.7	556.8	539.5	435.3	464.0	593.5	575.1
Sub total	1567.0				2,067.9			
Energy Center	electricity			480.5	-		-	
	kerosene			3,009.4				
Natural gas	-		-		-			616.0
Total	5057.0				2683.9			

* CO_2 emission: 0.36kg CO_2/kWh electricity, 2.51kg CO_2/L kerosene, 2.15kg CO_2 /m^3 natural gas

The cost of electricity in Table 6 is 12.1 yen/kWh. This is based on the fees charged for the East area by the electric power company over the past several years. The electric power cost is set by contract. So the cost of electricity in Table 6 differs from that of Table 4.

Other environmental aspects that were evaluated were NO_x and SO_x emissions. Assumptions were as follows: 1.35 g of NO_x was emitted per litter of kerosene combustion, based on the results of NO_x

emission tests. Weight fraction of S of kerosene used is assumed to be 40ppm. In the exhaust gas emitted by the Energy Center, NO_x is mainly NO_2 and SO_x is mainly SO_2. And, the amount of NO_x and SO_x emitted during the production of 1 kWh of electricity in Japan is 0.28 g and 0.23 g, respectively (JMA 2005). When NO_x from the small natural gas boilers is ignored, the total weight of NO_x and SO_x is reduced from 3.9 to 2.9 t. The precise weights of NO_x and SO_x are 2,832 kg and 1,077kg, respectively, for the old system and 1,608 kg and 1,321 kg, respectively, for the new system. Because the Energy Center used low-sulphur kerosene as fuel, the reduction of pollutants is achieved mainly from reduced NO_x emissions from the electric power generation plant.

5 CONCLUSIONS

Energy saving effects were estimated for a new heating and cooling system installed in laboratory buildings of the East area of AIST Tsukuba. The heating and cooling system was converted from central cooling and heating to a distributed system. The main effects of the system change are primary energy savings of 37 TJ, cost savings of 44.7 million yen and CO_2 emission reduction of 2 .4 kt per year. These effects will be achieved mainly through the use of high COP heat pumps, the reduction of ventilation loss by reduced fresh-air intake and the on-site installation of heat source equipment.

This reconstruction is the case where energy and cost saving and environmental aspects would be improved at a time. And there exist several more advanced systems that can utilize energy more efficiently, but AIST Tsukuba has come one step closer to more efficient energy usage.

The estimation was made possible by assuming the space conditioning loads of both heating and cooling. This estimation and assumptions will be corroborated after the completion of an energy consumption measuring system for the new system, which is scheduled for the end of FY 2004.

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