Smart Water Fund

Final Report

Water Conservation by Replacing Cooling Towers

52M-2108

20/3/2012

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Executive Summary

This report presents a study on applications of polymer heat exchangers to rejecting waste heat from a number of industrial processes. A plan for implementing the new waste heat rejection system in power stations and medium to large air-conditioning systems has been presented and issues likely to arise when implementing the plans have been identified.

It has been found that polymer heat exchangers have great potential for replacing some of the air-cooled heat exchangers currently used in power plants, medium to large air-conditioning systems and air-handling units in central air-conditioning systems.

It has been concluded that in the short term, the adoption of the polymer heat exchangers by power plants in Australia is unlikely because:

- power plants currently pay a very low price for water used, and
- the responsibility of providing reliable power supplies to the community will restrict power plants adopting new technologies.

It has been found that the polymer heat exchangers can be immediately used to replace the metal heat exchangers in the hybrid cooling systems used as coolers and air-handling units in large air-conditioning systems. With polymer heat exchangers, not only can the cost of the hybrid cooling systems be reduced but also the performance can be improved because water can be directly sprayed or distributed on to the polymer surfaces, reducing the need for special coatings or evaporation pads and reducing the fan power required.

It has been found that exposures to biocidal concentrations of hypochlorite would not be expected to affect the polypropylene (PP) flute boards to any extent. The PP flute board and spacer materials used in the construction of the cooling systems in this project would be expected to be stable under the normal operating conditions.

Further research is required to select the polymer materials to handle high pressures when using polymer heat exchangers for cooling refrigerant gases. Care is also needed to ensure that there is no detectable loss of refrigerant gas at such high pressures since the loss of refrigerant is a serious issue and it must be prevented at all cost.

In order to develop the air-cooled polymer heat exchangers into commercial products, further research is needed to develop techniques and manufacturing processes to fabricate water tight polymer heat exchangers.

To gain market acceptance of the polymer heat exchangers, it is necessary to find an industry partner to test the performance of the polymer heat exchangers in field applications.

Contents

1. BACKGROUND

Over 100 GL of fresh water, or 25% of Melbourne's water consumption, is lost annually through cooling towers in power stations and large air-conditioning systems in Victoria. This makes cooling towers one of the largest industrial consumers of fresh water. Currently power stations and large air-conditioning systems use cooling towers to reject waste heat. The waste heat is carried by warm water which is normally sprayed, evaporated and mixed with cooling air inside cooling towers. The cooling air together with the evaporated water is rejected to the ambient and thus water is lost by cooling towers. By eliminating water losses through cooling towers, valuable fresh water can be saved for the Victorian community. Cooling towers around Melbourne not only lose fresh water, but they are also the sources for the outbreaks of Legionnaires' disease. Because of these considerations, new technologies which are able to reduce water consumption and create a safe environment would benefit the community greatly. The project "Water Conservation by Replacing Cooling Towers" is to develop such technologies with the aims of designing and studying a new waste heat rejection system which consists of a highly compact heat exchanger made of polymer materials, studying the feasibility of replacing cooling towers in power stations and large air-conditioning systems by this new system and establishing its operational parameters.

The project has been funded by the Smart Water Fund over three years. So far, we have completed all the experiments and simulations for the polymer heat exchangers we built. This is the final report of the project.

This project started with the concept of using polymers as the materials of building heat exchangers for heat transfer between water and air. The advantages of polymer materials include their low cost, corrosion resistance and easy fabrication in comparison with metals such as aluminium and copper which are the main materials of building heat exchangers for industrial applications.

We have fabricated three heat exchangers using polypropylene flute boards, two counter flow heat exchangers and one cross flow heat exchanger. Due to the difficulty in preventing water leaks, we conducted experiments mainly on the counter flow heat exchangers. The experiments were conducted both in a laboratory at Victoria University and in the field at Yallourn power station. The experiments at Victoria University were for simple air cooling while the experiments at the Yallourn power station were for both simple air cooling and hybrid cooling in which the performance is enhanced using water evaporation. The experimental results from the VU laboratory were presented to the Smart Water Fund in Milestone 5 report and the experimental results from the Yallourn power station were presented to the Smart Water Fund in reports for Milestones 6 and 7.

Here we will develop plans for implementing the new waste heat rejection system in power stations, large air-conditioning systems and other areas of applications for the air-cooled polymer heat exchangers, and identify issues in implementing these plans.

2. CURRENT TECHNOLOGIES FOR REJECTING WASTE HEAT AND AREAS OF APPLICATIONS OF AIR-COOLED HEAT EXCHANGERS

Waste heat rejection is required in many industries such as power stations, large-air conditioning systems, chemical and food processing industries as well as in many service industries. Two large areas of application are in cooling power stations and in large air-conditioning systems.

2.1 Power stations

In power stations, several cooling technologies are available including once-through cooling, wet-recirculating cooling, dry cooling and hybrid cooling [1]. Table 1 from Dr Harlan Bengtson (http://www.brighthub.com/engineering/mechanical/ articles/ 64576.aspx) shows the percentages of different types of cooling technologies used in different US power plants (coal fired, non-coal fossil fired, combined cycle and nuclear) and Table 2 shows the typical water consumption for each MWh of electricity generation from the different types of power stations using different types of wet cooling technologies including once-through, pond cooling and cooling towers.

The once-through system generally withdraws very large amount of water from water bodies such as the sea, lakes or rivers to cool the power plants and the water is returned at an elevated temperature to the water body. The cooling of the power plants is achieved through sensible heat gain of the cooling water. Not only can some water be lost through evaporation (evaporative water loss associated with once through systems as a result of increased evaporation losses from the receiving water body surface caused by the differential temperature increase of the thermal plume), but additionally the water body is affected by the elevated temperature.

Wet-recirculating cooling uses mechanical draft or natural draft cooling towers. The cooling is mainly achieved through the evaporation of water and latent heat gain. In comparison with once-through systems, these cooling towers withdraw only a small amount of water [1] from the water body to replenish the water lost through evaporation. The amount of water loss through this evaporation from each power station using cooling towers is still quite large (in the order of many Giga Gallons per year). Chemical treatment of the cooling water [2] and visual plumes are some of the issues in using cooling towers.

Air-cooled condensers are used for direct dry cooling (condensing the exhaust steam directly) and indirect dry cooling (cooling the water which condenses the exhaust steam) [3]. For dry cooling, there is no water loss because either water is flowing in a closed loop or direct air cooling to the steam. The heat rejection is achieved through the sensible heat gain of air forced through the air-cooled condensers by fans of large diameters. These air-cooled condensers are normally made of metals which results in high capital cost [1], especially with the recent rapid increase of metal prices on the world market. The operating cost from the power consumption for driving the fans is also high in comparison with cooling towers [1]. In general, there will be thermodynamic cycle efficiency penalties in using air-cooled condensers in comparison with using wet-recirculating cooling towers when the ambient temperature is high [1].

Hybrid cooling is a combination of dry cooling and wet-recirculating cooling. When the ambient temperature is low, only dry cooling is needed to reject the heat from the turbine exhaust steam. When the ambient temperature is high, water can be sprayed in front of air-cooled condensers to reduce the temperature of the air flowing across the condenser tubes (there are other methods of achieving the hybrid cooling in this situation) [4]. By carefully setting the temperature at which water sprays are initiated, up to 95% of cooling water can be saved in comparison with using wet-recirculating cooling only and there will be less cycle efficiency penalties in the performance of the power plants in comparison with using dry air cooling only.

In Australia, electricity is generated mainly in coal fired power plants, and the majority of their cooling is achieved by cooling towers. Also, the majority of cooling towers in Australia are the natural draft type with a very high capital cost. Recently, air-cooled condensers have been used in a few power stations such as Darling Downs combined-cycle power station, Kogan Creek coal-fired power station and Millmerran power stations, all in Queensland.

Table 1 Percentage of different types of cooling used in different types of power plants (http://www.brighthub.com/engineering/mechanical/ articles/64576.aspx)

Generation Type	Percentage (%)			
	Cooling Tower	Once Through	Air-cooled Condenser	Cooling Pond
Coal	48.0%	39.1 %	0.2%	12.7%
Fossil Non-Coal	23.8%	59.2 %	0.0%	17.1%
Combined Cycle	30.8%	8.6%	59.0%	1.7%
Nuclear	43.6%	38.1%	0.0%	18.3%
Total	**41.9%**	**42.7%**	**0.9%**	**14.5%**

Table 2 typical water consumption for different types of wet cooling from Dr Harlan Bengtson (http://www.brighthub.com/engineering/mechanical/ articles/64576.aspx)

Steam Power Plant & Cooling System Type	Water Withdrawal (gal/MWh)	Typical Water Consumption (gal/MWh)
Fossil/biomass/waste fueled once-through cooling	20,000 to 50,000	~300
Fossil/biomass/waste fueled pond cooling	300 to 600	300-480
Fossil/biomass/waste fueled cooling tower	500 to 600	~480
Nuclear fueled once-through cooling	25,000 to 60,000	~400
Nuclear fueled pond cooling	500 to 1100	400-720
Nuclear fueled cooling tower	800 to 1100	~720

2.2 Large air-conditioning systems and other applications of air-cooled condensers

Large air-conditioning systems are mainly used in office buildings, hospitals, hotels, shopping centres, factories, food retails and trades and processing industries. Here, as in power stations, cooling technologies such as cooling towers, air-cooled condensers and hybrid cooling are in use to maintain the desired conditions.

Apart from rejecting waste heat for large air-conditioning systems, air-cooled heat exchangers have also been used in air handling units in large central air-conditioning systems as shown in Appendix A (Figures A1 and A2) where the heat exchangers are used to transfer cooling (heating) duty from refrigeration (heat pump) units to circulating air for cooling (heating), air cooled condensers for medium size air-conditioning systems (Figure A3) and air cooled heat exchangers for medium to small size refrigeration and HVAC cooling (Figure A4). In all these applications, the maximum temperature of the fluid is less than 60°C. Other applications of air-cooled heat exchangers include:

- Forced and induced draft air cooled heat exchangers
- Recirculation and shoe-box air cooled heat exchangers
- Hydrocarbon process and steam condensers
- Large engine radiators
- Turbine lube oil coolers

- Turbine intercoolers
- Natural gas and vapor coolers
- Combustion pre-heaters
- Flue gas re-heaters

Figure 1 shows a schematic of a central air-conditioning system with water-cooled chillers where the central air-handling unit is shown. The air-handling unit conditions and supplies air to the conditioned space. In Figure 1, a cooling tower is used to reject the heat generated by the condenser and can be replaced by air-cooled heat exchangers or a hybrid cooling unit. In the schematic, air is taken by the air-handling unit either from outside or from the space itself through a return air unit and two heat exchangers are used, one for heating and the other for cooling.

Figure 2 shows a schematic of a packaged air-conditioning system used for cooling an office. Here two heat exchangers are used, one as the cooling coil and the other as a condenser. In general, the energy requirement for cooling is very high and Figure 3 shows that in US alone [6], 1.4 Quads (10^{15} BTU) of primary energy is consumed by cooling annually.

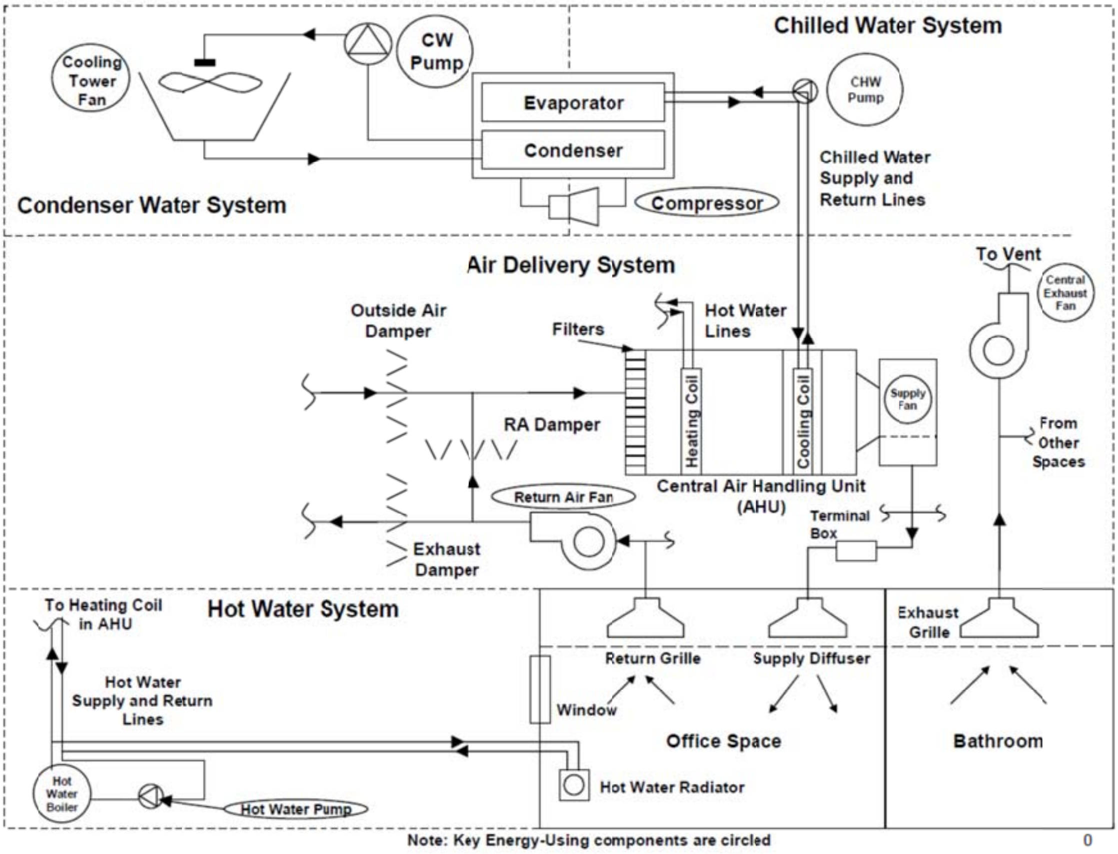

Figure 1 Schematic of a central system with water-cooled chiller [6]

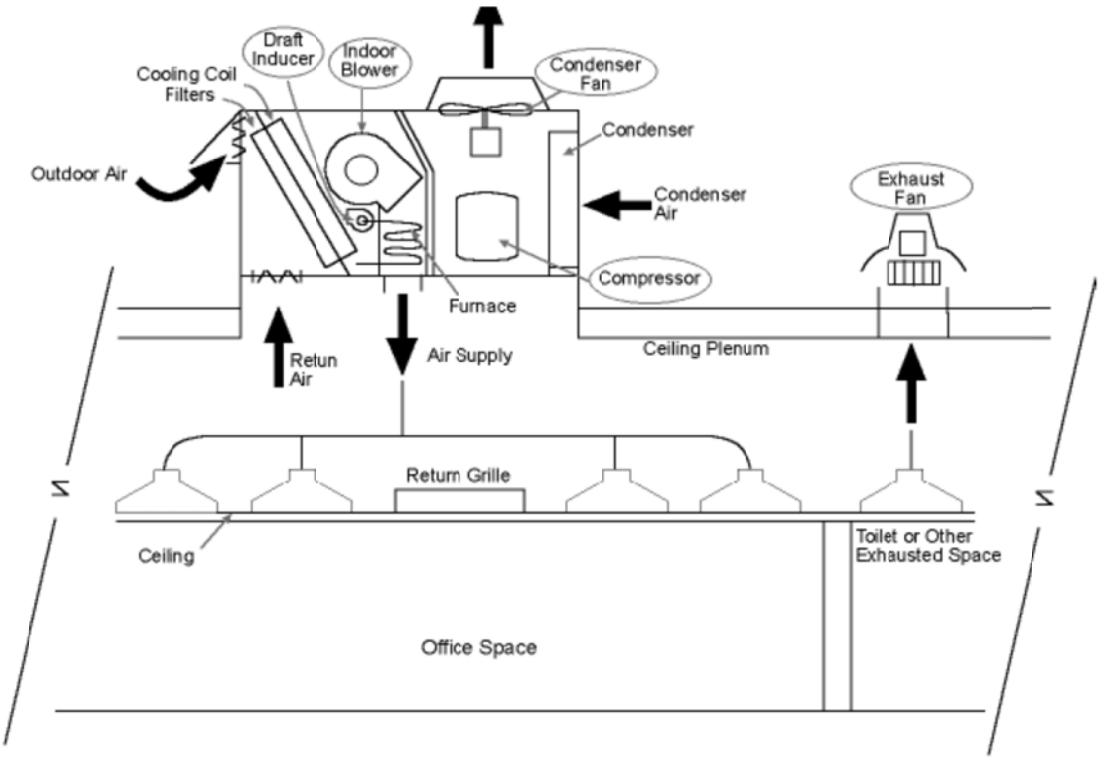

Figure 2 schematic of a packaged system [6]

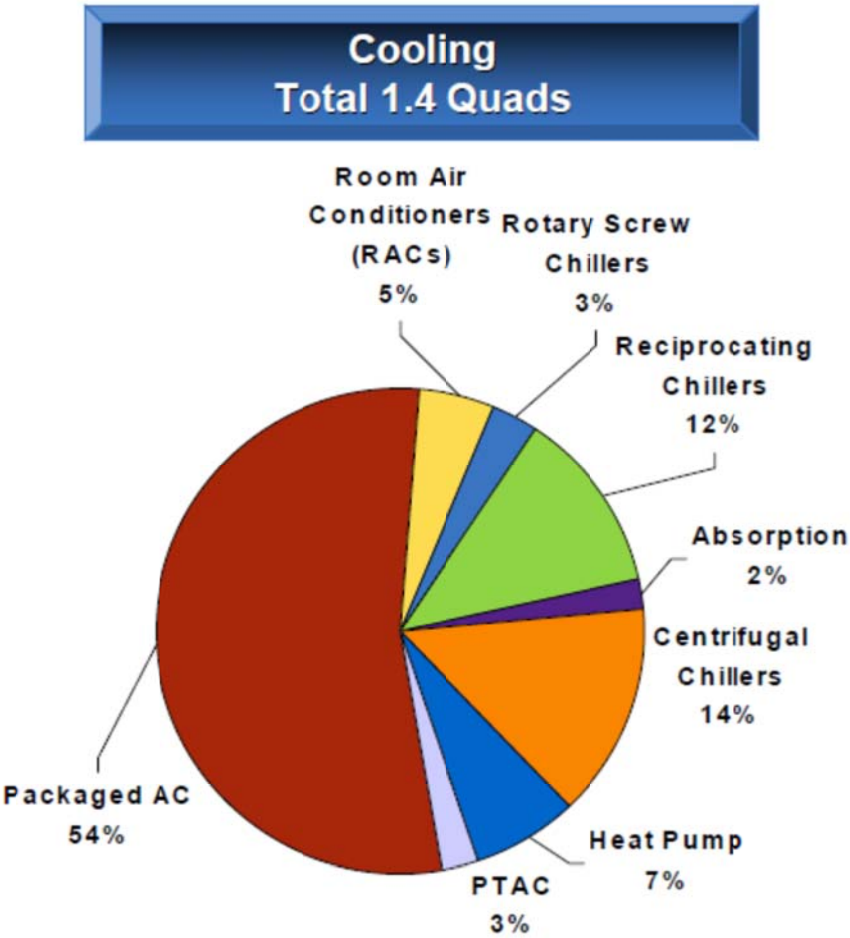

Figure 3 Primary energy consumption for cooling in the US [6].

3. ECONOMIC EVALUATION OF AIR-COOLED SYSTEMS FOR POWER STATIONS BASED ON CURRENT METAL HEAT EXCHANGERS

Although Table 2 shows that, among the different wet cooling technologies, once-through cooling consumes the least amount of water, its use has been declining. One reason for this is that the warm water it returns to the water body has an environmental impact and government legislation has restricted its use in power plants.

Table 1 shows that the percentage of cooling by US power plants that use air-cooled condensers is currently about 1%. The Electric Power Research Institute (EPRI) of USA has conducted a series of studies to compare the cost of replacing the once-through cooling by wet cooling (cooling towers) or air-cooled condensers [1]. It is found that to replace all the current once-though cooling by wet-cooling requires $95 billion US dollars. It also found that in general the costs of air-cooled systems are much higher than wet cooling systems (forced draft cooling towers) in terms of capital and annualized costs.

Table 3 from [1] shows the annual cost of using a wet cooling system for a 500 MW combined-cycle power plant by assuming an electricity price of $35/MWh, a water cost of $1.00/kgal and an amortization factor of 8%. In the US, mainly forced draft wet cooling towers are used because of the very high initial capital cost of natural draft cooling towers. Table 3 presents the costs at five sites for a range of environmental conditions. The cooling duty for the 500 MW combined-cycle power plants is equivalent to that of a 170 MW steam power plant. Figure 4 shows the comparison of capital costs between the optimized wet cooling and dry cooling for the same 500 MW combined-cycle power plant and Figure 5 shows the ratios of capital costs between the dry and wet cooling systems. It can be seen that in general the capital cost of dry cooling systems is about 3 to 4 times that of the wet cooling systems. Figure 6 shows the annual costs for the optimized wet and dry cooling systems [1] and Figure 7 shows the ratios of annual costs between the dry and wet cooling. Again, the annual cost of dry cooling systems is about 3 to 4 times that of wet cooling systems.

The costs shown in Figures 4 to 7 are based on a cost of water of $1.00/kgal (about $0.25/m^3$). Figure 8 shows the effect of water price on annual cost ratios [1] between dry and wet cooling systems. Figure 5 indicates that it is only when the water price is increased to above $2.00/kgal (about $0.5/m^3$), the annualized cost of dry cooling systems can be less than that of wet cooling systems.

Table 3 Complete wet cooling systems annual cost for combined-cycle

Costs for Optimized Wet Systems at Five Sites					
	Site 1 Hot, arid	Site 2 Hot, humid	Site 3 Arid, extreme	Site 4 Moderate, cool	Site 5 Moderate, warm
Approach, F	12.5	7.5	12.5	12.5	12.5
Range, F	22.5	15	20	22.5	17.5
Capital Cost	$5,775,000	$6,452,000	$5,796,000	$5,705,000	$5,822,000
Annualized Capital Cost	$462,000	$516,160	$463,680	$456,400	$465,760
Annual Fan Power, HP	$465,000	$647,000	$499,000	$465,000	$538,000
Cost of Capacity Shortfall	-$60,000	-$60,000	-$60,000	-$60,000	-$60,000
Maintenance Cost	$115,500	$129,040	$115,920	$114,100	$116,440
Water Cost	$910,000	$910,000	$910,000	$910,000	$910,000
Total	$1,892,500	$2,142,200	$1,928,600	$1,885,500	$1,970,200

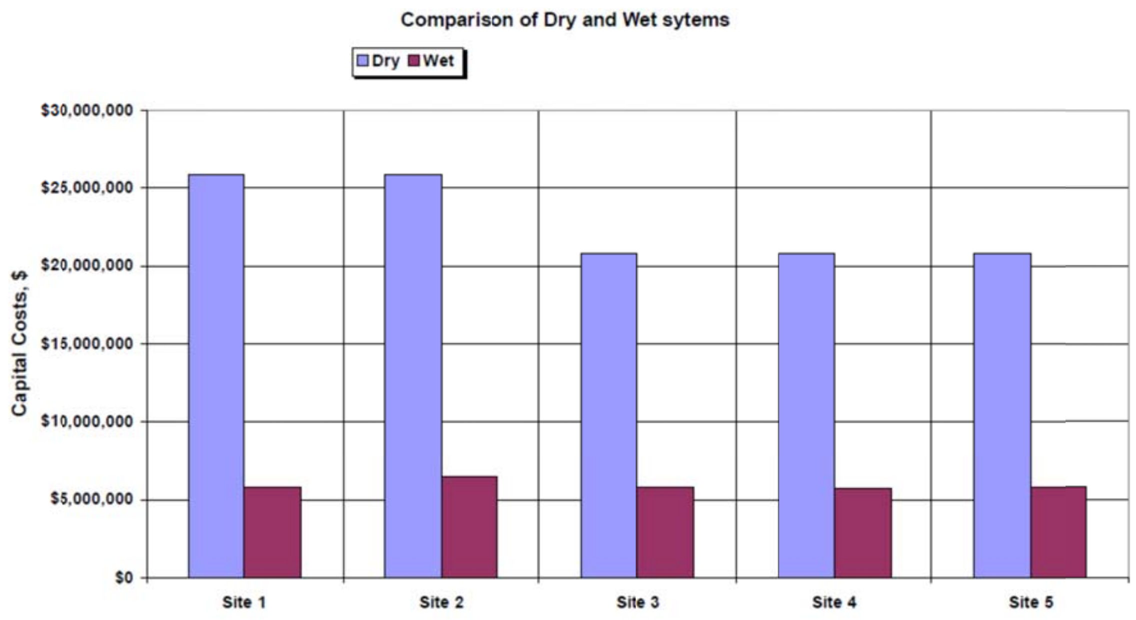

Figure 4 Capital cost comparison of optimized wet and dry cooling system [1]

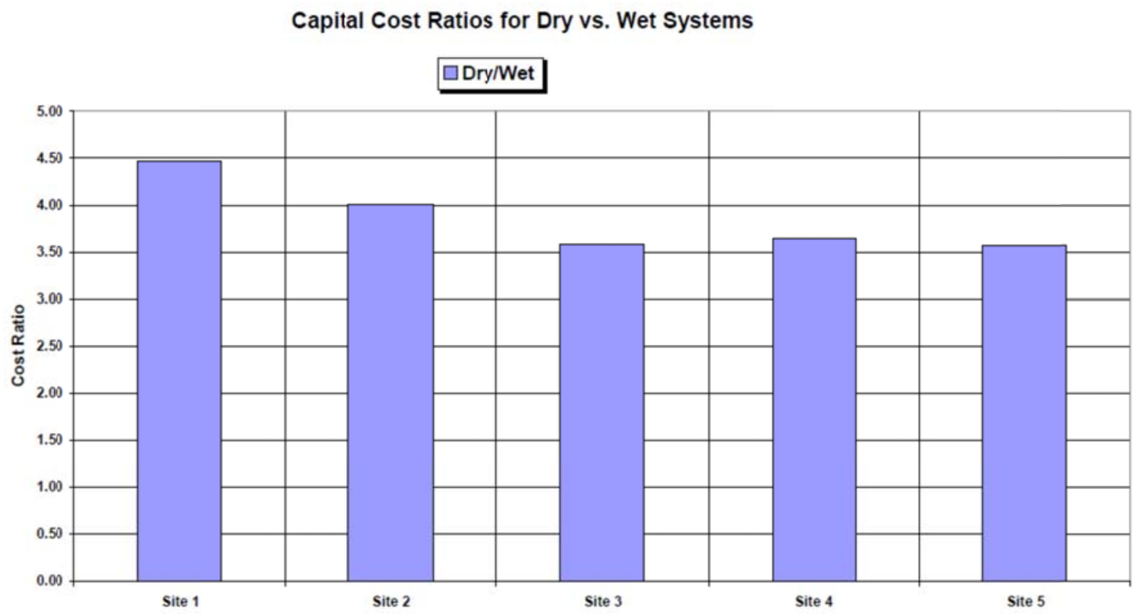

Figure 5 Capital cost ratios for optimized wet and dry cooling systems [2]

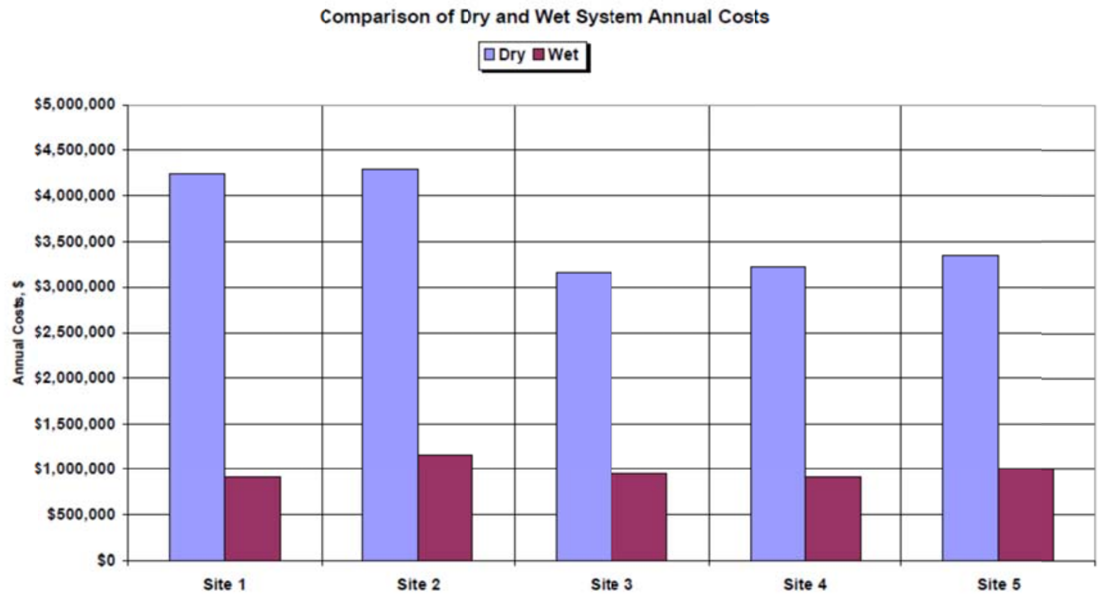

Figure 6 Comparison of annual costs for optimized wet and dry cooling systems [1]

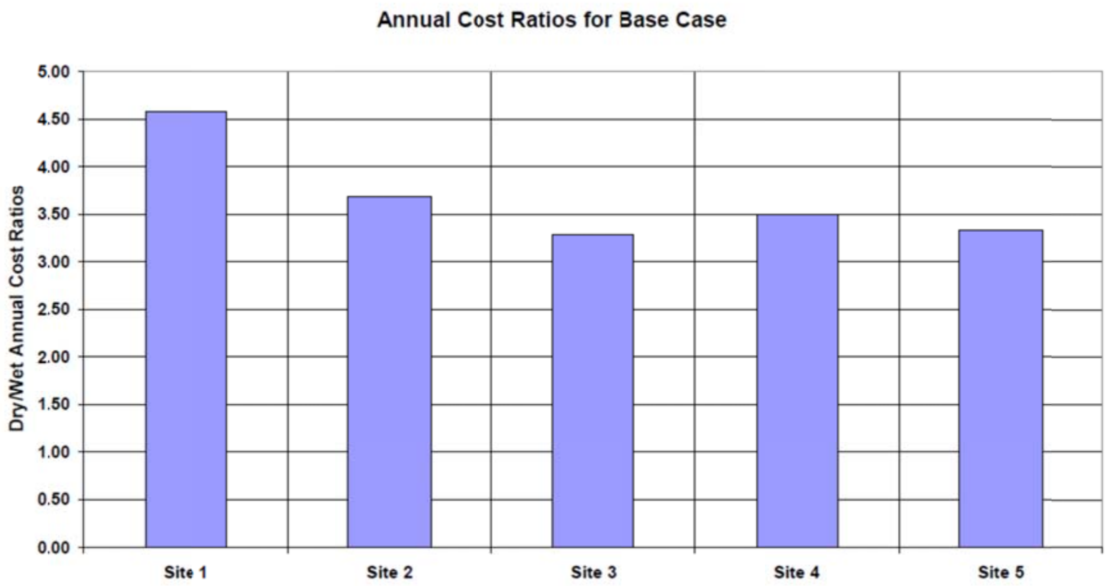

Figure 7 Ratio of annual costs for optimized wet and dry cooling systems [1]

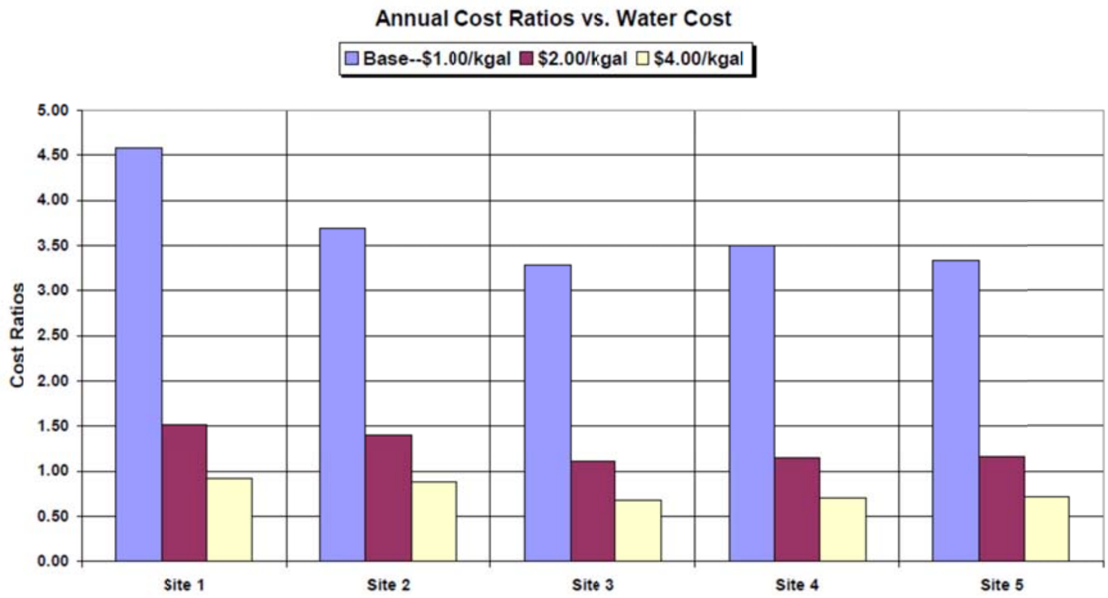

Figure 8 Effect of water price on annual cost ratios [1]

In selecting cooling methods for power plants, the capital and annualized costs constitute only one set of considerations. As pointed in [1], "Where drought or population growth leads to present or projected shortages of water for agricultural, residential, commercial and industrial use or for in-stream flow maintenance, opposition to power plants frequently focuses on the issue of water use. The use of alternative water-conserving cooling systems is frequently proposed and occasionally mandated as a condition for approval". Other concerns include a desire to reduce impacts on aquatic organisms, to eliminate any discharge streams or to avoid problems with visible plumes drifting from wet cooling towers. Even though the cost estimation given in Figures 4 to 8 show large differences between wet and dry cooling systems, the increase in the overall cost of electricity is relatively small. Table 4 from Dr Harlan Bengtson shows that the overall power production cost from using wet cooling systems is about 1.9% higher than that of once-through systems (the lowest cost among the various cooling techniques), and that of dry cooling systems is 4.9% higher than that of once-through cooling systems. The difference in producing electricity between that using the wet cooling systems and that using dry cooling systems is thus about 3%.

Table 4 Cost difference of wet and dry cooling systems in comparison with a once-through cooling system (http://www.brighthub.com/engineering/mechanical/articles/64576.aspx)

Items for Comparison	Type of Cooling System		
	Once Through	Wet Tower	Dry Cooling
Capital Cost	base	base + 0.4%	base + 12.5%
Cooling System Power	base	base + 2.5 MW	base + 3.0 MW
Plant Heat Rate	base	base + 0.4%	base + 4.0%
Power Production Cost	base	base + 1.9%	base + 4.9%

4. COST COMPONENTS OF AIR-COOLED SYSTEMS IN POWER PLANTS

Figure 9 from [3] shows the air-cooled cooling system used at the El Dorado power plant and Figure 10 [3] shows a schematic diagram of an air-cooled condenser (ACC) for power plants. As according to [3], the main cost components for an air-cooled condenser include:

1) finned-tube bundle systems consisting of heat exchangers, finned tubes, and associated headers;

2) structures to support the finned-tube bundle systems as well as motor and fan systems;

3) steam ducting for transporting steam from the turbine exit to the air-cooled condensers;

4) air removal system for removing non-condensable gas from the steam and this is required for all air cooling systems;

5) mechanical equipment including fans, fan drives (motors) and gearboxes.

Table 5 from [3] gives the relative cost breakdown of the various components of an ACC system. Table 5 shows that the cost percentage for heat exchanger bundles is about 32% for a total system cost of $600,000. According to Figure 1, the capital cost of dry cooling systems for a 500MW combined-cycle power plants exceeds $20 million. It is expected that, as the size of the system is increased, the relative cost of the heat exchanger bundles will be higher than the 32% given in Table 5 since the relative costs for structural steel, steam ducting, transportation and other servicing components will decrease. Estimation using the data given in [1] shows that the heat exchanger bundles and the mechanical (fans and motors) can account up to 70% of the total cost of the air-cooled system for a 170MW electricity generation by the steam turbine from a combined 500MW combined cycle power plant. After removing the cost for the mechanical components, it is expected that for such a large air-cooling system, the cost for the heat exchanger bundles would be about 65% that of the total air-cooled system.

Table 5 Typical air-cooled condensers component cost breakdown [2]

Component	% Cost	Est. $
Heat Exchanger Bundles	32.0%	$ 192,000
Structural Steel	16.0%	$ 96,000
Casing	0.5%	$ 3,000
Fan Inlet Bell	0.9%	$ 5,400
Ducting	6.0%	$ 36,000
Expansion Joints/Bellows	1.3%	$ 7,800
Piping	1.5%	$ 9,000
Mechanical Equipment	5.4%	$ 32,400
Air Removal Pumps	1.4%	$ 8,400
Valves and Instrumentation	0.5%	$ 3,000
Drain Pumps & Rupture Disc	0.1%	$ 600
Condensate Tank / "Decorator Dome"	0.2%	$ 1,440
Shipping (U.S. Destination)	11.0%	$ 66,000
Engineering/Project Mgmt.	5.0%	$ 30,000
Subtotal	81.8%	$ 491,040
Overhead, Contingency, Profit	18.2%	$ 108,960
Total	100.0%	$ 600,000

Figure 9 Air-cooled cooling system at El Dorado generating station [2]

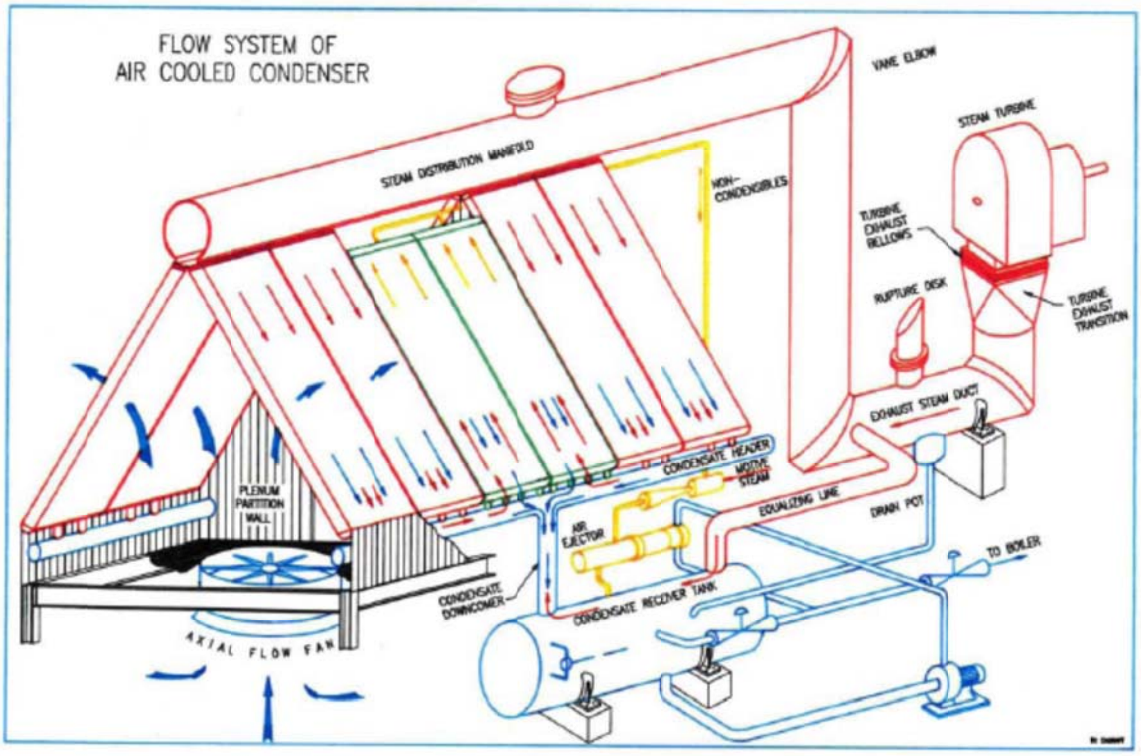

Figure 10 Schematic of an air-cooled condenser for power plant [2]

The above discussion has focused on wet cooling and simple dry cooling systems. The two cooling technologies can be combined to form hybrid cooling systems with evaporative cooling being required only when the ambient temperature is high. Although the capital cost of a hybrid cooling system may be slightly higher than that of a dry cooling system, its annualized cost will be much less than that of simple dry cooling systems because a large contribution to the annualized cost for using dry cooling system arises from a shortfall in capacity, especially in hot arid environments as indicated in Table 6 [1].

Table 6 Cost of ACC at five sites for a 500MW combined cycle power plant [1]

Costs for Optimized ACC's at Five Sites					
	Site 1	Site 2	Site 3	Site 4	Site 5
	Hot, arid	Hot, humid	Arid, extreme	Moderate, cool	Moderate, warm
Design ITD	46.1	41.1	51.1	51.1	51.1
Capital Cost	$23,022,000	$25,816,000	$20,774,000	$20,774,000	$20,774,000
Annualized Capital Cost	$1,841,747	$2,065,000	$1,662,000	$1,662,000	$1,662,000
Annual Fan Power	$1,137,331	$1,325,000	$888,000	$975,000	$936,000
Cost of Capacity Shortfall	$929,870	$509,000	$298,000	$273,000	$437,000
Maintenance Cost	$345,328	$387,000	$312,000	$312,000	$312,000
Water Cost	Base	Base	Base	Base	Base
Total	$4,254,000	$4,286,000	$3,160,000	$3,222,000	$3,347,000

5. ECONOMIC EVALUATION OF AIR-COOLED SYSTEMS FOR AIR-CONDITIONING BASED ON CURRENT METAL HEAT EXCHANGERS

Gert Dierks and Stephen Fairgrieve [5] have undertaken a technical and economical evaluation of cooling systems incorporating refrigeration and air-conditioning technology for a refrigeration plant in Frankfurt city centre. They compared an open loop evaporative cooling tower, an open evaporative cooling tower with an intermediate heat exchanger, a closed loop evaporative cooling tower with an intermediate heat exchanger, a closed loop evaporative cooling tower, an air-cooled heat exchanger with co-current water spray cooling, an air-cooled heat exchanger with counter-current fogging and a hybrid dry cooling system as shown in Figure 11.

In the detailed technical and economic evaluation [5], some of the above mentioned cooling technologies were excluded due to technical difficulties in meeting the cooling requirement and corrosion of the equipment. Tables 7 and 8 are the results [5] from the technical and economic evaluation of the selected four cooling technologies. It can be seen from these evaluations that the hybrid dry cooling system is the preferred choice, both technically and economically.

The cost estimations given in Table 8 are based on a heat load of 630 kW to be removed from the condenser and rejected to the environment. When the same evaluations are undertaken in Australia, the cost of water would be less since the cost of water in Australia is about $1.0/m^3$ which is about half of that shown in Table 8. Table 9 shows the results in Australia by using a water price (including the waste water cost and water treatment) as half of that in Europe while the cost of other components have been kept the same. Table 9 shows that in Australia, the annual cost of hybrid cooling systems is about half of that for the open loop evaporative cooling towers while in Europe it is about one third.

In Australia, Muller Industries manufactures hybrid cooling systems for large air-conditioning and refrigeration plants. Its working principle is shown in Figure 12 which is very similar to that shown in Figure 11. When the temperature of the ambient air is low, it cools the air conditioning units using the ambient dry air. When the temperature of the ambient air is high, water flows from the top of the pre-cooled evaporation pads and wets the pads. As air flows through the wetted evaporation pads, its temperature drops below the ambient temperature to close to that of the ambient wet bulb temperature as it becomes saturated with water vapour before entering the heat exchangers. This will result in an increased temperature difference between the warm water flowing inside the copper tubes and the saturated air flowing across the aluminium fins of the heat exchangers so that the designed heat rejection capacity can be achieved without increasing the power consumption associated with driving the fans to force additional air through. In comparison with air-cooled heat rejection only, some water will be lost from these hybrid cooling units. By properly selecting the temperature at which water starts flowing in the hybrid cooling units, up to 80% of water can be saved in comparison with air conditioning systems using cooling towers. Thus the systems developed by Muller Industries consume less power during hot summer days in comparison with dry air-cooled systems and they save water in comparison with those using cooling towers since they use water for a fraction of the time in comparison with that in operating cooling towers.

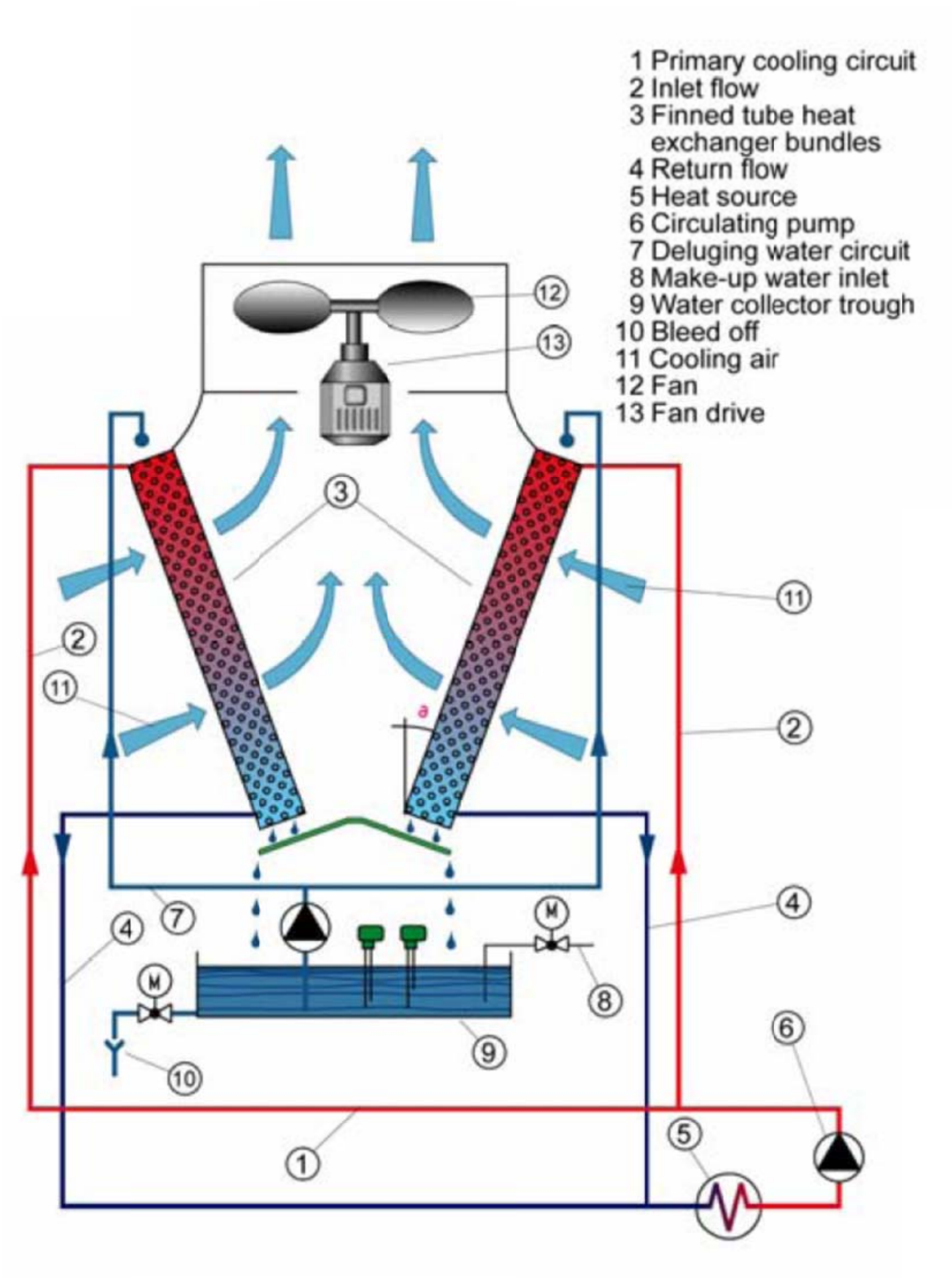

Figure 11 A schematic of hybrid dry cooling system from [5]

Table 7 Cooling system technical evaluation [5]

		Solution 1		Solution 2		Solution 3		Solution 4	
Evaluation criteria (VDI 2225)	Wgt. Factor	Open loop evaporative cooling tower	Pts	Closed loop evaporative cooling tower	Pts	Air-cooled heat exchanger with fogging	Pts	Hybrid dy cooling system	Pts
Space requirements LXWXH (base area)	3	2.7X3.5X3.5 (9.45m3)	10	5.3X2.8X3.75 (14.8m3)	9	2X6.7X3.2X3.5 (42 m3)	5	5.4X2.44X3.7 (13.18m3)	9
Operating weight	3	5825kg	10	12000kg	3	11000kg	3	6640	9
Make-up water (evaporative)		7885to/yr		7885		2300to/yr		2547to/yr	
Make-up water (blowdown)		7885 to/yr		7885 to/yr		0		849 to/yr	
Make-up water (drift losses)		0.79 to/yr		0		0		0	
Total make-up water	4	15770 to/yr	2	15770 to/yr	2	2300 to/yr	10	3396 to/yr	8
Circuit water contamination	3	yes	2	no	10	no	10	no	10
Fan power requirement	4	3.5kW	10	27kW	2	28.8kW	2	8.4kW	7
Freeze protection heater power requirement	3	2.0kW	3	2.0kW	3	0	10	0	10
Internal pump power requirement	3	0	10	3.6kW	4	5.0kW	3	0.55kW	7
Visible plume	4	yes	2	yes	2	no	10	no	10
Number of fans	2	1	4	1	4	6	2	2	7
Maintenance	2	2 day/yr	7	3 days/yr	6	2 days/yr	7	2 days/yr	7
Corrosion protection	4	Good	7	Good	7	Satisfactory	5	Extremely Good	8
$Points_{tot}$=Wgt Factor X pts	35		211		159		219		295

Table 8 Cooling system economical evaluation [5]

		Solution 1	Solution 2	Solution 3	Solution 4
Type of cost		Open loop evaporative cooling tower	Closed loop evaporative cooling tower	Air-cooled heat exchanger with fogging	Hybrid dry cooling system
Procurement value, incl.					
Assembly and commission	EURO €	17100,00	37500.00	90675.00	72500.00
Depreciation period	Years	15	15	15	15
Interest rate	%	5	5	5	5
Annuity	%	9.63	9.63	9.63	9.63
Make-up water costs	EURO/m3	2.20	2.20	2.20	2.20
Waste water costs	EURO/m3	1.73	1.73	1.73	1.73
Water treatment	EURO/m3	0.60	0.60	0.60	0.60
Blowdown concentration factor		2	2	0	3
Power costs	EURO/kWh	0.13	0.13	0.13	0.13
Total water cost	EURO/year	71438.00	71438.00	10419.00	15384.00
Power costs	EURO/year	1613.00	15928.00	20199.5	5808.00
Maintenance costs	EURO/year	1250.00	1875.00	1250.00	1250.00
Capital costs	EURO/year	1647.00	3611.50	8232.00	6982.00
Total annual cost	EURO/year	75948.00	92852.50	40100.50	29424.00

Table 9 Adjusted cost annual cost in Australia for different cooling solutions

		Solution 1	Solution 2	Solution 3	Solution 4
Type of cost		Open loop evaporative cooling tower	Closed loop evaporative cooling tower	Air-cooled heat exchanger with fogging	Hybrid dry cooling system
Total cost of water	EURO/year	35,719	35,719	5,210	7,692
Total annual cost	EURO/year	40,265	57,134	34,891	21,732

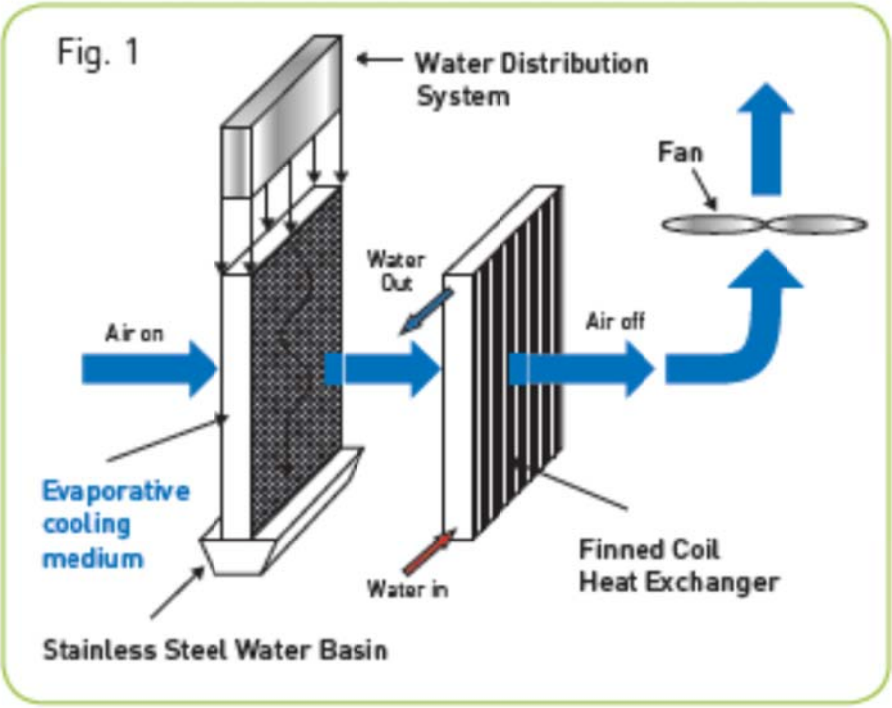

Figure 12 The working principle of the hybrid cooling from Muller Industries

Examination of the systems shown in Figures 11 and 12 reveals that there are some differences. In Figure 11, water is directly sprayed (or distributed) onto the heat exchangers while that in Figure 12, water is distributed onto evaporation pads. To prevent corrosion, heat exchangers as shown in Figure 11 need to be coated with a protective paint. In Figure 12, water liquid will not be in contact with the heat exchangers, thus avoiding corrosion. Figure A5 in Appendix A shows a photo of a 3C Cooler from Muller Industries. The large evaporation pads are clearly visible.

Figure 13 from Muller Industries shows a comparison of costs between the cooling tower, air-cooled condensers and its 3C Cooler units. In figure 13, the price of electricity and water are assumed to be \$0.15/kWh and \$1.00/m^3, respectively In Figure 13, the capacity of the air-cooled heat exchanger for the Muller Industries 3C Cooler is smaller than that for the simple air-cooled condenser because the high demand for cooling (occurs during hot summer days) can be met by the evaporative cooling when the 3C Cooler unit is used.

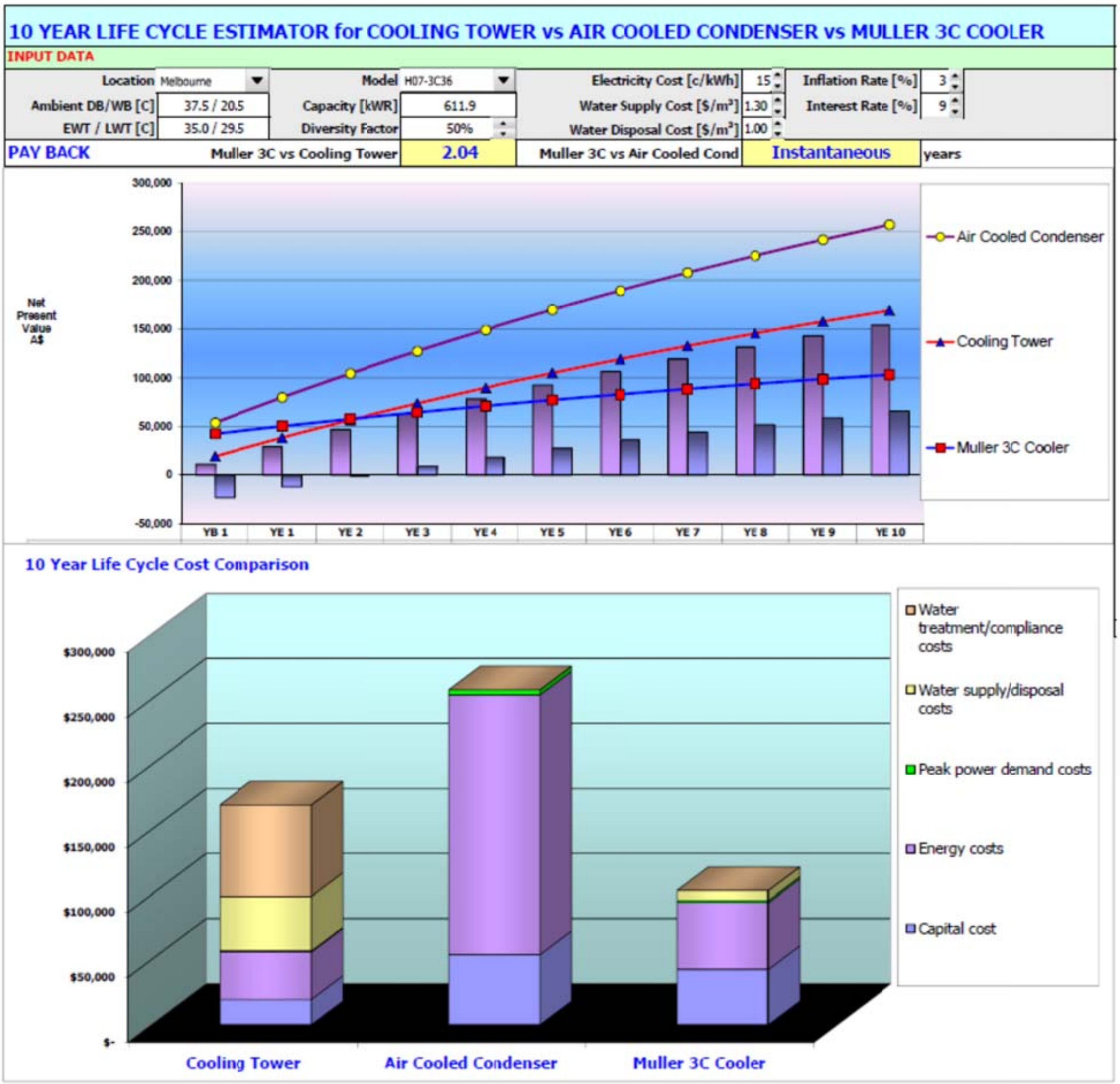

Figure 13 cost comparison between cooling tower, air-cooled condenser and Muller Industries 3C Cooler for a capacity of 610kW.

Although the 3C Cooler unit compares favourably with the other two cooling technologies for large air-conditioning systems, a comparison with that shown in Figure 11 shows that the 3C Cooler from Muller Industries will consume more electricity since energy is required to push the air across the evaporation pads all the time. A discussion with Muller Industries indicated that this may result in a 30-40% increase of electricity consumption in comparison with that using no evaporation pads. The advantages of using evaporation pads include avoiding corrosion of the heat exchangers and the pads can act as filters to protect the heat exchangers so less maintenance is required for the heat exchangers.

6. MARKET SIZE FOR AIR-COOLED HEAT EXCHANGERS

As can be seen from the above, the market size for air-cooled heat exchangers (condensers) is very large. Table 10 [6] shows the major HAVC equipment manufacturers with total market size for the US in 1996.

Table 10 Major HAVC equipment manufacturers [6]

Product	Major Companies	Total Market Size ($Million) 1996
Air-Handling Units[1]	Trane York Carrier McQuay Dunham Bush	775
Central System Terminal Boxes[1]	Titus Trane ETI	144
Fan-Coil Units[1]	IEC Trane McQuay	92
Classroom Unit Ventilator[1]	Trane McQuay	120
Cooling Towers[1]	Baltimore Air Coil Marley Evapco	400[3]
Pumps[2]	Taco Bell & Gosset Paco	250

Sources: 1. BSRIA/Ducker, October 1997 (Reference 4)
2. Based on discussions with manufacturers

Notes: 3. Does not include evaporative condenser and closed-circuit evaporative coolers. Does include many cooling towers used in industrial applications.

According to a report by Global Industry Analysis, Inc., the global market size for Cooling Towers is projected to reach US$1.8 billion a year by 2015 (mainly the cooling towers used for large air-conditioning systems). A study by York International Corporation shows that in 1995, the world market size for air-conditioning and refrigeration systems is about $22 billion and would increase to $150 billion by 2005 as demand from developing countries increases. Figure 14 shows the market sizes of heat exchangers in China and the world as according to THTI. The heat exchangers include plate heat exchangers, shell-and-tube heat exchangers, air-cooled heat exchangers, weld plate heat exchangers, heat exchanger unit and plate-and-shell heat exchangers. Air-cooled heat exchangers constitute only one of the many types of the heat exchangers but THTI also suggested that in China, air-cooled systems are replacing water-cooled systems, reducing water consumption which is an important consideration in Northern China and as a result air-cooled heat exchangers have immense potential for growth.

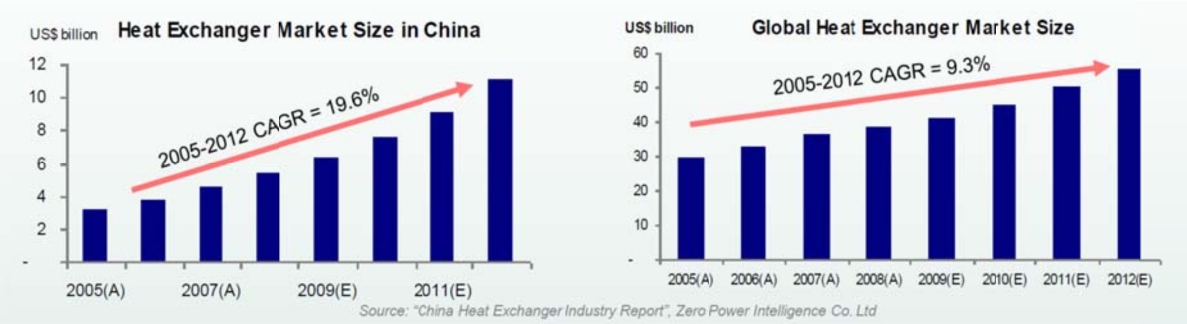

Figure 14 Heat exchanger market sizes in China and the world as according to THTI.

7. COMPETETIVE ADVANTAGES OF POLYMER HEAT EXCHANGERS

The main advantage of using air-cooled heat exchangers made of polymers is their low cost. The current market price for aluminium, the commonly used material for building air-cooled heat exchangers for power plants, large air-conditioning systems, air-handling units and air-cooled condensers, is about $2,700/MT and that of low cost polymer materials is about $1,350/MT. The density of aluminium is 2,700kg/m^3 and that of polymer materials is about 1,000kg/m^3. The price/volume ratio between the aluminium and the polymer materials is thus 5.4 using current market prices. In building highly compact heat exchangers, it is the surface area or the volume (for a given fin or wall thickness) rather than the mass of the material that contributes to the heat transfer. Thus, in terms of raw materials, it is expected that the cost of building compact polymer heat exchangers will be about 20% of that of using aluminium. This will result in a significant difference in the cost of purchasing air-cooled heat exchangers for the same heat transfer surface area.

It can also be expected that the cost of manufacturing the polymer heat exchangers will also be lower because in extruding polypropylene (one of the polymers that can be used in building polymer heat exchangers) into flute boards, temperature of less than 300°C is required while temperature at least of 1000°C is needed in manufacturing aluminium heat exchangers.

Other advantages of using polymer heat exchangers in comparison with those built using aluminium include corrosion resistance, less fouling, less weight for the same surface area of heat transfer and easier to clean. For example, because of the corrosiveness of the polluted water in some industries, heat exchangers made of stainless steel have to be used even though the highest temperature encountered by the heat exchangers is less than 60°C. This has resulted in a very high cost of the units. With heat exchangers built from polymer materials, this polluted water can be handled easily.

It is expected that the air-cooled polymer heat exchangers will be used at low temperature (<70°C) and low pressure (<250kPa) operating conditions. The temperature and pressure encountered in cooling for power plants, large air-conditioning systems and air-handling units are well within the temperature and pressure limits of most polymer materials. The thermal conductivity of polymers is generally between 0.15 and 0.45 W/mK and considered low. But for air-cooled heat exchangers, the resistance to heat transfer is dominated by thermal resistance in the air channels, and the resistance resulting from the polymer materials is negligible. We have confirmed this by using computational fluid dynamics (CFD) simulations and found that the total heat rejection capacity from a polymer heat exchanger is less than that from an aluminium heat exchanger of same size by no more than 2.5% at the same operating conditions, even though the thermal conductivity of the aluminium is about 1,000 times that of common polymer materials.

One issue with heat exchangers built using polymers is that they may not last as long as those made from using aluminium, especially when the condensers are exposed to direct sunlight. However, sunlight inhibiting agents can be added to the polymers to prolong their life. Also, protection measures for the heat exchangers from direct sunlight exposure can be built into each individual heat exchanger or in the final overall system. A discussion on the stability of polymer materials, based on a study undertaken by Dr Marlene Cran of the Institute for Sustainability and Innovation of Victoria University, is given in Appendix B. The results show that normal exposures to biocidal concentrations of hypochlorite would not be expected to affect the polypropylene (PP) flute boards to any extent. The PP flute board and spacer materials used in the construction of the cooling system during this project would be expected to be stable under normal operating conditions.

8. PLANS FOR IMPLEMENTING THE NEW WASTE HEAT REJECTION SYSTEMS

8.1 Replacing cooling towers in power plants

Since the late 1990s, air-cooled condensers have been increasingly used for cooling power plants due to the requirement to conserve water and concerns over the environmental impacts of wet cooling. Currently, commercially available air-cooled condensers are constructed from metals and are very expensive in terms of capital cost and operational cost (high energy consumption). Because of this, power plant and large air-conditioning system operators are reluctant to use air-cooled condensers made of metals. Recently, the American Electric Power Research Institute (EPRI) has made developing Advanced Cooling for power plants as its top priority research area in the next 6 to 8 years.

In replacing the cooling towers by air-cooled condensers, many concerns need to be considered before decisions can be made to adopt the polymer heat exchangers:

(1) Capital cost
By using the price difference between aluminium and polymer materials, it is expected that the cost of the heat exchanger bundles made of polymer materials will be about 20% of that aluminium. Since the cost of heat exchanger bundles can account for 65% of the total cost of the dry cooling systems as mentioned above, it is expected that the total capital cost of air-cooled cooling systems for power plants will be half of the current capital cost of using aluminium heat exchanger bundles. This is because the cost of fans, motors, supporting structures and steam ducting will be expected to remain the same irrespective what material is used for fabricating the heat exchanger bundles. Using the results given in Figure 2, it is expected that the capital cost of an air-cooled cooling system using polymer heat exchanger bundles will still be twice as expensive as that of using cooling towers.

(2) Operating cost
The operating cost includes the cost of power for driving the fans (both the wet cooing for forced draft type cooling towers and the dry cooling systems) and pumps (for wet cooling systems), the cost of water and its treatment (wet cooling), the cost of maintenance and the cost of capacity shortfall (dry cooling systems). Tables 3 and 6 from [1] show the total annual costs for wet system and air-cooled system for a 500MW combined-cycle power plant for five sites of different environment conditions. The prices for electricity and water are assumed to be $35/MWh and $1.00/kgal, respectively. The results in Tables 3 and 6 show that the annualized cost for the air-cooled system (with metal heat exchangers) is in general more than twice as high as that for wet cooling.

Table 11 compares the annualized cost of wet cooling systems and the air-cooled systems of using metal heat exchangers and polymer heat exchangers for Site 1 as given in Tables

3 and 6 (hot arid environment). It can be seen from Table 11, the ratio of the annualized cost between the air-cooled systems and that of wet cooling systems has been reduced from 2.25 to 1.76 when the metal heat exchangers are replaced by polymer heat exchangers.

Table 11. Annualized cost of wet cooling and air-cooled systems with metal and polymer heat exchangers for Site 1 given in Tables 3 and 6.

Cost comparison between wet cooling, air-cooled condensers made of metals and polymer materials			
	Wet cooling	Air cooling	Air cooling
		Metal (Aluminium)	Polymer materials
Capital cost	$5,775,000	$23,022,000	$11,510,000
Annualized Capital cost	$462,000	$1,841,747	$920,873.5
Annual power cost	$465,000	$1,137,331	$1,137,331
Cost of capacity shortfall	-$60,000	$929,870	$929,870
Maintenance cost	$115,500	$345,328	$345,328
Water cost	$910,000	base	Base
Total annualized cost	$1,892,500	$4,254,000	$3,333,420.5
Cost ratio	1.0	2.25	1.76

(3) Plant cycle efficiency penalty

Currently, one issue of using air-cooled condensers for power plants is the plant cycle efficiency penalty in comparison with using wet-recirculating cooling systems when the ambient temperature is high. This is mainly due to the fact that wet-recirculating cooling system relies on wet bulb temperature of the ambient air and simple air-cooling systems rely on dry bulb temperature. When the ambient temperature is high, as on hot summer days, the heat rejection capacity of a simple air-cooled system will be reduced due to the smaller temperature difference between the steam to be condensed and the ambient air. This will result in a temperature increase in the condensate and the back pressure of the turbine and a reduction in the energy efficiency of the turbine. Because of this, the turbine will not be able to produce as much electricity and this will result in a penalty on plant thermodynamic cycle efficiency. Worse still, this happens at a time when electricity is in high demand and profit margin of the power plants is at the highest during a year. Also, the designed initial temperature difference (ITD) for simple air-cooled condensers is in general higher than that for wet-recirculating cooling in order to reduce the capital cost of purchasing the air-cooled condensers made of metals.

One solution to reduce the plant cycle efficiency penalty is to use hybrid cooling systems similar to those shown in Figures 8 and 9. Our experimental results from the Yallourn power station (as presented in the Milestone 7 report) show that with hybrid cooling, the cooling capacity of the air-cooled system can be maintained the same as the wet cooing system and that a water saving up to 95% can be achieved for power stations in the Latrobe Valley. Table 14 shows the effect of using hybrid cooling on the annualized cost. In Table 14 we have assumed that only 80% of water can be saved in comparison with that of wet cooling systems and we assume that the cost of water distribution systems for the evaporative cooling is low in comparison with other major components. It can be seen from Table 14 that with hybrid cooling systems, the annualized cost ratio for cooling a

500MW combined cycle power plant can be reduced to 1.37 (relative to that of wet cooling).

Table 12 Annualized cost of wet cooling, air-cooled systems with metal heat exchanger bundles and hybrid cooling with polymer heat exchangers for Site 1 given in Tables 3 and 6.

Cost comparison between wet cooling, air-cooled condensers made of metals and hybrid cooling with polymer heat exchangers			
	Wet cooling	Air-cooled cooling	Hybrid cooling
		Metal (Aluminium)	Polymer materials
Capital cost	\$5,775,000	\$23,022,000	\$11,510,000
Annualized Capital cost	\$462,000	\$1,841,747	\$920,873.5
Annual power cost	\$465,000	\$1,137,331	\$1,137,331
Cost of capacity shortfall	-\$60,000	\$929,870	base
Maintenance cost	\$115,500	\$345,328	\$345,328
Water cost	\$910,000	base	\$182,000
Total annualized cost	\$1,892,500	\$4,254,000	\$2,585,532.5
Cost ratio	1.0	2.25	1.37

(4) High temperature
Condensers built from polymers cannot be used in high temperature conditions, especially commonly available low cost polymers. In cooling power plants, the temperature of the turbine exhaust steam is in general less than 70°C (9.2 in. Hga back pressure, typical guidelines are: “alarm” @ 7.0 in. Hga, “trip” @ 8.0 in. Hga [7]). This is well within the continuous operation temperature range (90°C-120°C) of most polymers available If using indirect air-cooling (air is used to cool the recirculating water rather than exhaust steam), the maximum temperature of the fluid entering the air-cooled condensers can be controlled to be less than 50°C.

(5) Power consumption of the cooling systems
Power is required to operate the cooling systems. In wet cooling, this is required to drive the fans (for forced draft cooling towers) and to pump the cooling water to and from the cooling towers (natural draft cooling towers). In simple air cooling, it is used mainly for driving the fans. In hybrid cooling, it is used for driving the fans and pumping water for spraying (or water distribution which requires less pressure and thus less power).

In designing the polymer heat exchangers, the fan power consumption based on the calculated pressure drop and flow rate is about 100W for a 25 kW heat rejection as shown in the report for Milestone 3. It is expected that the fan power for driving the polymer heat exchangers will be less than that of metal heat exchangers because the air flow in polymer heat exchangers is laminar while that in metal heat exchangers is in general turbulent flow. In the experiments conducted at Yallourn power plant, we measured the air pressure drops across the heat exchanger and the air flow rates. From this, it has been estimated that the fan power consumption is about 135W for a heat rejection of 15kW. The reason for this increase of heat rejection/fan power in comparison with the designed fan power of 100W for 25kW heat rejection is due to the low water flow rates (<0.19kg/s) and low temperature (<45°C) of the warm water entering the heat exchanger in the field experiments. In contrast, the design conditions are: water flow rate of 0.25kg/s and water temperature of 50°C entering the heat exchanger. Also, the air flow rate for the experiments at Yallourn power station is about 10% higher than that of the designed condition. Using the experimental data from the Yallourn power station (given the above considerations, this is an over estimation), it can be estimated that, for a 500MW combined-cycle power plant, the fan power required for the polymer heat exchangers as air-cooled condensers will be about 3MW. The average fan power is about 4MW as given in [1] for the same power plant using air-cooled metal heat exchangers.

When applying the polymer heat exchangers to directly condense the steam from the power plants (direct cooling), it is expected that the power consumption will be less than that estimated using the experimental data from Yallourn power station. This is because the steam is in general at a higher temperature than the cooling water from the power plants during our experiments and the temperature change of the steam during condensation is small (theoretically it should be zero) as it flows through the air-cooled condenser as in direct cooling. This is unlike cooling water because its temperature decreases significantly as it flows through the heat exchanger, thus reducing the average temperature difference between the warm water and the cooling air. Because of this, it is expected that the temperature difference between the steam and the air will be much higher on average than that between the air and the cooling water. The large temperature difference in directly cooling steam will enhance the efficiency of the heat exchangers and thus less fan power will be required.

However, to be confident about the power saving of using polymer heat exchangers in comparison with that of using metal heat exchangers, further studies are required, especially for large air-cooled condensers

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(6) The Australian situation
As mentioned above, in Australia, most of large power plants use natural draft cooling towers for cooling. Because of their high capital cost, it is expected that future power plants will be less likely to use natural draft cooling towers if evaporative cooling is still the preferred choice of cooling. Currently, the water price for power stations is very low and water entitlements are generally allocated for the life of the power plants. Thus, economically, it is not appealing for power plants to use air-cooled condensers unless the power plants are located inland. Also, power plants are required to provide reliable power supplies to the community and will be very reluctant to adopt new technologies. It is believed that, at least in the short terms, Australian power stations will not be likely to use polymer heat exchangers to cool their power plants.

8.2 Replacing cooling towers in large air-conditioning systems
As the results in Tables 8 and 9 and those in Figure 11 show air-cooled condensers are more cost effective than wet cooling towers. The reason for this, in contrast to that in power plants, is that the water price in urban areas is in general much higher than that for power plants.

Polymer heat exchangers are well suited to be employed in hybrid cooling systems for large air-conditioning systems because of their low cost and the operating temperature and pressure are well within the limits of the commonly used polymer materials. Also, because the polymer materials have better corrosion resistance than most metals, water can be sprayed or distributed onto the heat exchangers directly. No special coatings is required, there will be no need for evaporation pads such as those used in Muller Industries' 3C Cooler units hence less fan power will be required..

We approached Muller Industries to collaborate on further development of the polymer heat exchangers for use in their hybrid cooling systems. Muller Industries initially agreed to be part of the team to apply to the Smart Water Fund but withdrew at the last minute due to a change of ownership of the company (Muller Industries was taken over recently by an American company).

An issue concerning hybrid cooling for large air-conditioning systems is the space required to install the cooling system. As shown in Table 7, hybrid cooling systems require a slightly larger space than wet cooling systems.

8.3 Replacing air-cooled condensers for medium size air-conditioning systems

Polymer heat exchangers can be used for air-cooled condensers for medium size air-conditioning systems if the pressure is within the limits of the polymer materials used to build the polymer heat exchangers. In most of the air-cooled condensers for air-conditioning systems, refrigerant gas rather than liquid water is to be cooled. In this case, the pressure of superheated refrigerant gas is on the order of 1MPa which is much higher than the limit of the pressure that can be applied to the polypropylene flute boards used in this study. Other polymer materials may be more suitable in handling such high pressures. Care is also needed to ensure that there is no detectable loss of refrigerant at such high pressures since the loss of refrigerant is a serious issue and it must be stopped at all cost.

8.4 Replacing coils used in air-handling units

Coils in air-handling units are in general used to transfer heat from water to air or from air to air. The polymer heat exchangers are well suited to be used in the air-handling units to replace coils made of metals.

9. IDENTIFY ISSUES IN IMPLEMENTING THE PLANS

As air-cooled condensers, the polymer heat exchangers will have similar risks as those made of metals when they are used for cooling. The same measures applied to metal heat exchangers to minimize these risks also apply to the polymer condensers.

One of the risks for polymer heat exchangers is potential damage. To take full advantage of polymer heat exchangers (low cost and low density), the thickness of polymer walls in building the heat exchangers will be small. Because of this, it is possible that the walls can be damaged under direct impact by sharp objects and leaking of fluid from one stream to another might occur. This can be avoided by installing protective screens to cover the frontal external surfaces of the heat exchangers. Also, the heat exchangers can be built in small modules so that they can be replaced easily without interrupting the operation.

Technically, the leaking of water from the polymer heat exchangers needs to be prevented before the polymer heat exchangers can be used commercially. Techniques and manufacturing processes need to be developed to build watertight polymer heat exchangers. It is believed that such techniques and processes can be developed.

Because they are relatively new, polymer heat exchangers need to be thoroughly tested under various field conditions before they can be accepted by industries and consumers. It is believed that an industry partner like Muller Industries would be well suited to promote the polymer heat exchangers to the market.

10. CONCLUSIONS AND DISCUSSION

It has been found that polymer heat exchangers have potential in replacing some of the air-cooled heat exchangers currently used in power plants, medium to large air-conditioning systems and air-handling units in central air-conditioning systems.

However, they are unlikely to be used in power plants in Australia in the near term because currently power plants pay a low price for water and, because of their perceived responsibility to provide reliable power supplies to the community, they may not be disposed to adopting different approaches to cooling their plants.

It has been found that the polymer heat exchangers can be immediately used to replace metal heat exchangers in the hybrid cooling systems used in large air-conditioning systems and the air-handling units. With polymer heat exchangers, not only the cost of hybrid cooling systems can be reduced but also the performance can be improved because water can be directly sprayed or distributed on the polymer surface, reducing the need for special coatings or evaporation pads and reducing the fan power.

Further research is required to select the polymer materials to handle high pressures when using polymer heat exchangers for cooling refrigerant gas. Care is also needed to make sure that there is no detectable loss of refrigerant gas at such high pressures since the loss of refrigerant is a serious issue and should be avoided.

It has been found that normal exposures to biocidal concentrations of hypochlorite would not be expected to affect the polypropylene flute boards to any extent. The PP flute board and spacer materials used in the construction of cooling systems are expected to be stable under normal operating conditions.

In order to develop air-cooled polymer heat exchanger systems into commercial products, further research is needed to develop techniques and manufacturing processes to build watertight polymer heat exchangers.

To facilitate market acceptance of polymer heat exchanger systems, it may be necessary to find an industry partner to test and demonstrate the performance of polymer heat exchanger systems in field applications.

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APPENDIX A SOME INDUSTRY SYSTEMS USING AIR-COOLED CONDENSERS

Figure A1 Air-handling unit from Air Change.

Figure A2 Air Handling unit from Carrier

Figure A3 Air-Cooled Condenser from TRANE for medium size air-conditioning system

Figure A4 Air cooled heat exchanger from Alfa Laval for refrigeration and HVAC cooling.

Figure A5 A photo of the Muller Industries' 3C cooling system

APPENDIX B

POLYMER MATERIAL STABILITY

Background

The polymer material used in the construction of the internal components of the cooling system is polypropylene (PP). This particular polymer belongs to the olefin-based polymers which includes polyethylenes and many rubbers. It is inherently strong, and resistant to a range of potentially stressing environmental conditions including moisture, heat, most chemicals and biological attack. Without adequate stabilisation, however, PP can be damaged by UV light. Although there are no known solvents for PP at room temperature, some chemicals are known to aggressively attack the material including some strong acids, some oxidising agents such as peroxide, and some chlorinated and aromatic hydrocarbons.

The large PP sections of the cooling system are a commercial extruded fluted PP twin-wall sheet which is commonly used for signage, in horticulture, for packaging, and a range of industrial uses. This material is corona treated to slightly oxidise the surface in order to facilitate printing and adhesion. The spacers used between the fluted PP sheets are also comprised of PP that has been corona treated.

The key features of PP fluted sheet include:

- Excellent water and heat resistance
- Light weight and easy processability
- Aging resistance and durability
- High tensile strength
- Chemical resistance and non-toxicity
- Easy to clean and maintain

- Recyclability and cost effectiveness

The cooling system developed in this project involves exposing one side of the PP fluted board to heated process water that is subsequently cooled by air from the other side. Typically, cooling tower water is disinfected by low concentrations of a chlorinated oxidant, hypochlorite. Although PP should not be adversely affected by hypochlorite at the low concentrations used in cooling tower water (0.1-0.5 ppm), the long-term effects of hypochlorite exposure on PP are unknown. This section of the study aimed to expose the PP flute board and PP spacers to accelerated ageing conditions of hypochlorite and heat in order to assess the potential long-term stability of the material under exposure conditions.

Experiments
Samples of the PP flute board were exposed to a temperature of 65°C in an air circulating oven for 120 days. Samples were also exposed to low and high concentrations of hypochlorite at 65°C for up to 30 days. The concentration of hypochlorite was maintained by daily addition of fresh hypochlorite.

Samples of PP before and after exposure were subjected to thermal analysis by differential scanning calorimetry (DSC), structural analysis by Fourier-transform infrared (FTIR) spectroscopy, and imaging by scanning electron microscopy (SEM).

Results
The 120 day oven aged sample of PP flute did not show any significant changes in morphology as shown by the similar DSC thermograms in Figure B1. The new PP flute shows a characteristic PP peak at *ca.* 165°C and also a very minor peak at *ca.* 120°C suggesting the presence of a copolymer that may enhance the mechanical strength of the material. Apart from a slight broadening of both the PP and copolymer peaks, oven ageing for 120 days at a moderate temperature does not appear to adversely affect the material.

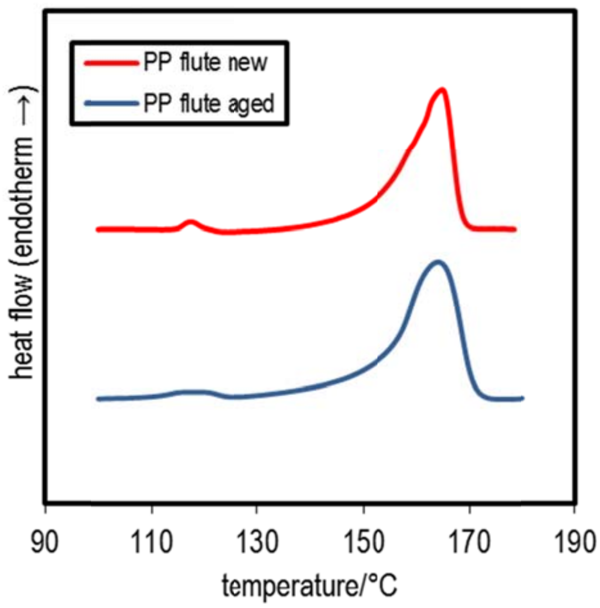

Figure B1 DSC thermograms of PP flute before and after oven ageing.

Figure B2 shows the FTIR transmission spectrum of the PP flute before and after 120 days oven ageing at 65°C in the wavenumber region 1785-1685 cm^{-1}. The key peak in this region is that at *ca.* 1740 cm^{-1} which represents the carbonyl peak. This peak is present when oxidation of the PP has occurred and a carbonyl index can be calculated to assess relative changes in the material with time. For minimally processed materials, the carbonyl peak is very minor but in this case, the new PP flute shows a significant peak. This confirms that the material has been corona treated which is a process to deliberately introduce oxidised sites on the PP surface to facilitate printing and adhesion. The aged PP flute does not show any significant change in the carbonyl peak suggesting that ageing at 65°C has not resulted in additional surface oxidation.

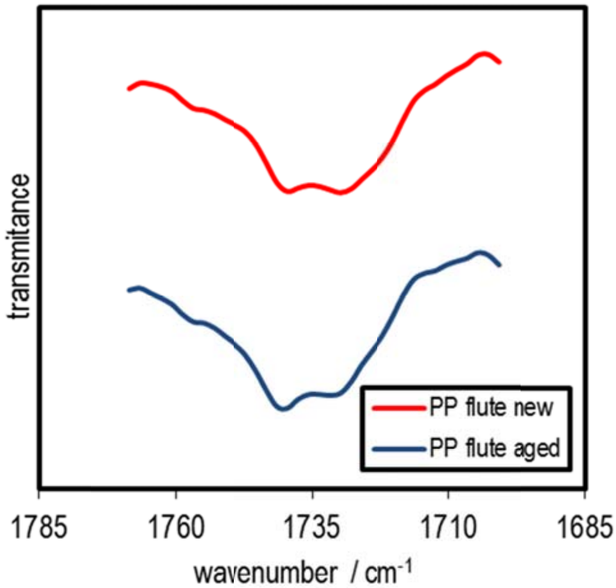

Figure B2 FTIR spectrum in the carbonyl band region before and after oven ageing.

Low Concentration Hypochlorite Exposure

A typical biocide concentration of hypochlorite in cooling tower water is 0.1-0.5 ppm. The concentration of available chlorine depends on factors such as chlorine demand and the presence of other chemicals or ions in the water. Figure B3 shows the change in normalised carbonyl index for the PP flute and PP spacer materials exposed to 1 ppm hypochlorite for up to 30 days. Only a very slight increase is observed for each of the materials with the black spacer material affected more than the other PP samples. This may be due to the presence of a pigment such as carbon black which may affect the oxidative stability under certain conditions. A carbonyl index of 3-4 would be considered a significant degradation so a change of only 1-2% does not represent a significant degree of oxidation.

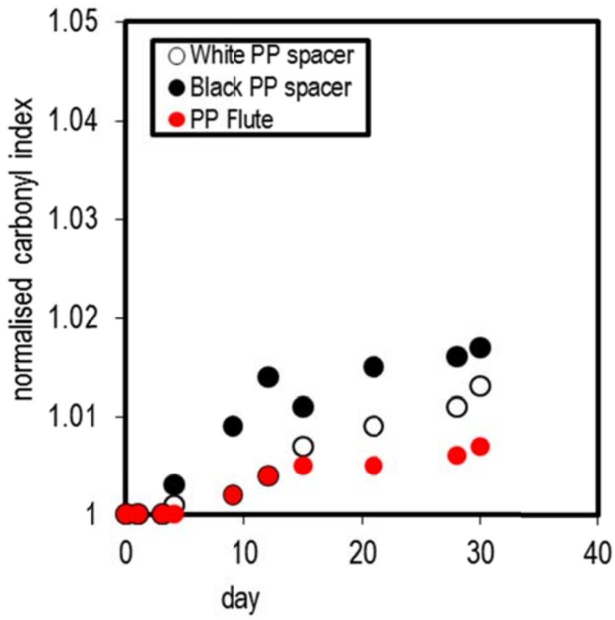

Figure B3 Change in carbonyl index with low concentration hypochlorite exposure.

High Concentration Hypochlorite Exposure

To assess the effect of high hypochlorite exposure, samples of the PP flute were exposed to 1000 ppm hypochlorite at 65°C for 10 days. The samples were then observed by SEM to observe any potential surface changes. Figure B4(a) shows the SEM image of the PP flute before exposure. The surface is relatively smooth with the presence of some impurities which could be pigment particles. The machine direction of the extrusion is evident by the feint vertical lines that are present in the image. In contrast, the sample exposed to a very high concentration of hypochlorite (Figure B4(b)) shows considerable changes that appear to be cracking and deterioration of the materials surface. Although visual inspection of the material only reveals a very slight discolouration, only high magnification imaging can reveal the extent of the damage imparted by the oxidant.

(a) (b)

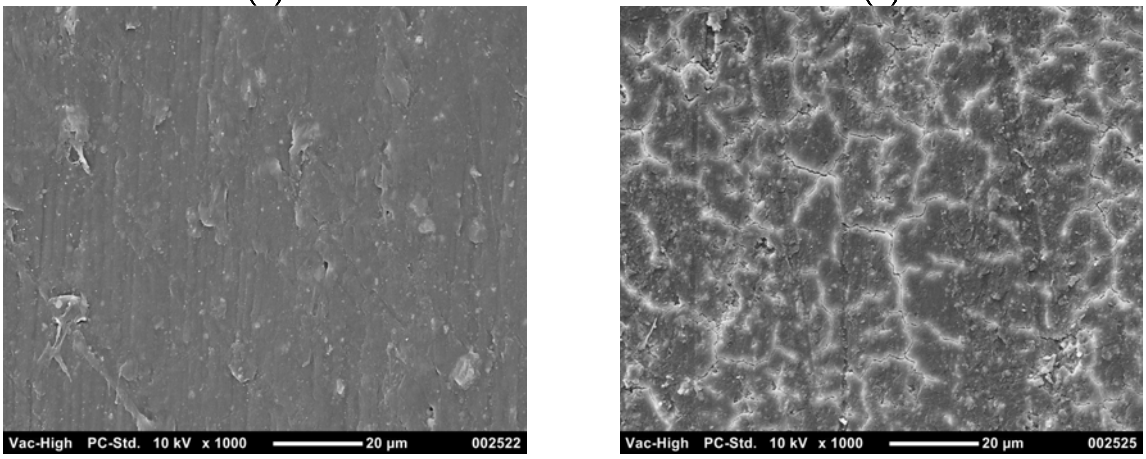

Figure B4 SEM images of PP flute (a) before and (b) after hypochlorite exposure.

The FTIR analysis of the PP flute before and after extreme hypochlorite exposure revealed a significant change in the carbonyl peak as shown in Figure B5. A carbonyl index > 3 was determined and is indicative of a substantial oxidative change in the material. The units ppm-hours are often used in industry to calculate the relative exposure of an agent with time and are equivalent to the product of concentration (ppm) and exposure time (hours). The hypochlorite exposure experienced by the PP flute in this experiment was *ca.* 240,000 ppm-hours, far greater than would be expected in normal operating conditions which would be in the order of 1000 to 2500 ppm-hours over a year. Moreover, there is no evidence to suggest that the ppm-hours are linear with time or concentration.

Summary

The PP flute did not undergo any significant oxidative change under moderate heating or with exposure to biocide concentrations of hypochlorite. Exposure to some extreme concentrations of hypochlorite resulted in some significant, observable oxidative changes in the PP flute material. Normal exposures would not be expected to affect the PP flute to any extent. The PP flute board and spacer materials used in the construction of the cooling system would be expected to be stable under the current operating conditions. The effect of UV exposure has not been studied and needs to be investigated before the polymer heat exchangers can be used for industrial applications where they are exposed to direct sunlight.

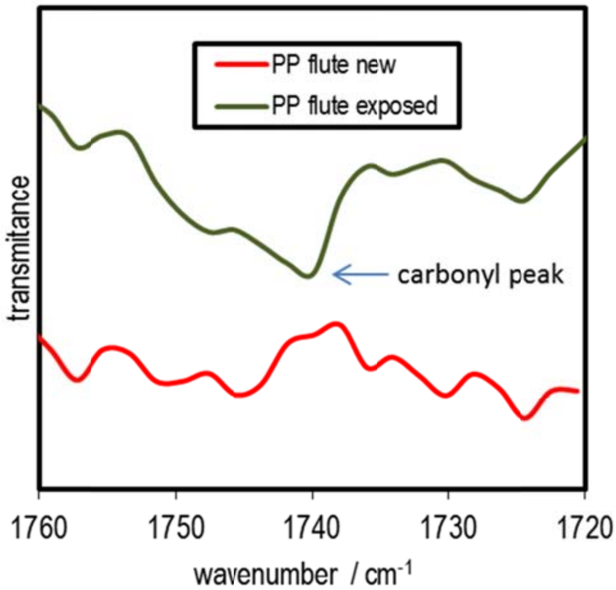

Figure B5 FTIR spectrum in the carbonyl band region before and after hypochlorite exposure.