University of Southern Queensland
Faculty of Engineering and Surveying

Validation of Cooling Grid Model and Testing of Alternatives

A dissertation submitted by

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in fulfilment of the requirements of

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towards the degree of

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Abstract

The Great Artesian Basin Sustainability Initiative, (GABSI), is a joint state and federal government project which rehabilitates artesian bores and replaces bore drains with polyethylene pipeline systems to tanks and troughs for stock water. The naturally pressurised artesian water can reach temperatures of up to 99˚C due to the heat convection at great depths within the Earth's crust. The heated artesian water is required to be cooled to below 45 ˚C to prevent heat deterioration of the polyethylene pipe and to maintain a 50 year design life of the entire reticulation system. Historically, a submerged network of copper pipes has been designed for each system to provide a cooling mechanism and maintain the natural pressure of the bore.

The project's main aim was to predict and confirm the heat transfer parameters for cooling grids submerged in water and air, investigate alternative cooling options and validate the design model to accurately reflect existing operation. The testing procedure utilised a 12 metre length of the three pipe materials under investigation, which were tested at four representative flow rates surrounded by air and then submerged underwater. Inlet, outlet, ambient and pond temperatures were monitored along with relative humidity and weather observations.

The experimental results and research allowed for model to be validated and deemed accurate with an appropriate factor of safety. The alternative designs tested were comparatively analysed accounting for costs, cooling performance, pipeline flow characteristics, material availability, corrosion resistance and maintenance requirements. Aluminium was determined to exhibit the most desirable traits and was recommended as the most suitable alternative cooling grid pipe material. Air as a heat transfer medium was deemed inappropriate for cooling artesian bore water because of the apparent lack of heat transfer.

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Signature

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Date

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CHAPTER 1

INTRODUCTION

1.0 Introduction

Artesian groundwater flowing to the surface from a 1 to 3 kilometre deep sandstone aquifer called the Great Artesian Basin, is an important natural resource and has provided a secure water supply for the settlement and development of expansive grazing areas throughout western Queensland, north-western New South Wales, north-east South Australia and the south-east Northern Territory. The free flowing groundwater can vary in temperature from 30 to 99 ° Celsius at the surface.

Historically, the water has been distributed across the landscape by gravity through earthen channels called ‘bore drains’. These extensive man-made networks of earth channels extend for tens to hundreds of kilometres across pastoral grazing properties to distribute this artesian water to previously uninhabitable (dry) regions to produce water stock animals. Without the requirement of cooling, the water has been allowed to flow uncontrolled under the action of gravity into the bore drain network which can service up to 200 kilometres from a single outlet. Although the system is effective in transporting water, the efficiency of water delivery is very low with as much as 97% of water flowing into the drains being lost to evaporation and seepage, not to mention the environmental impacts such as weed infestation, salinity and harbouring of feral animals caused by the drains themselves.

In addition to these high losses, as more bores have been drilled the natural pressure of the entire basin has dropped significantly, further highlighting the need for conservation to protect the sustainability of such an important natural resource.

The Great Artesian Basin Sustainability Initiative (GABSI) is a joint federal and state government project undertaken by the Queensland Government Department of Natural Resources and Water (DNR&W) which is tasked with ensuring the sustainability of the Great Artesian Basin. GABSI’s main aim is to limit wasteful losses from the basin by replacing bore drains with polyethylene pipes supplying tanks and troughs at designated watering points. The project also tests and inspects bores and bore casings, rehabilitating where necessary, to ensure efficient water delivery to the surface.

By replacing the open drains with polyethylene pipe, losses to evaporation and seepage are virtually eliminated, as are the surface environmental impacts created by the drains.

A water temperature of less than 45 ℃ will ensure a 50 year design life is achievable for the medium density PE 80B polyethylene pipe used to replace the bore drains. However, as the water flowing to the surface is still at a high temperature the water must be cooled before it enters the system to guarantee the polyethylene pipe will not degrade over time with the excess heat.

Cooling of the artesian water is achieved by the installation of a cooling grid. A typical cooling grid is a network of pressurised copper pipes arranged in a radiator type configuration through which the high temperature bore water is cooled and delivered to the pipe network distribution head. This grid is submerged in a pond at a depth of 2 metres where conductive, convective and evaporative cooling effects dissipate the heat from the artesian water cooling it to below 45 ℃ before delivery to the polyethylene pipe system (see Figure 1.1).

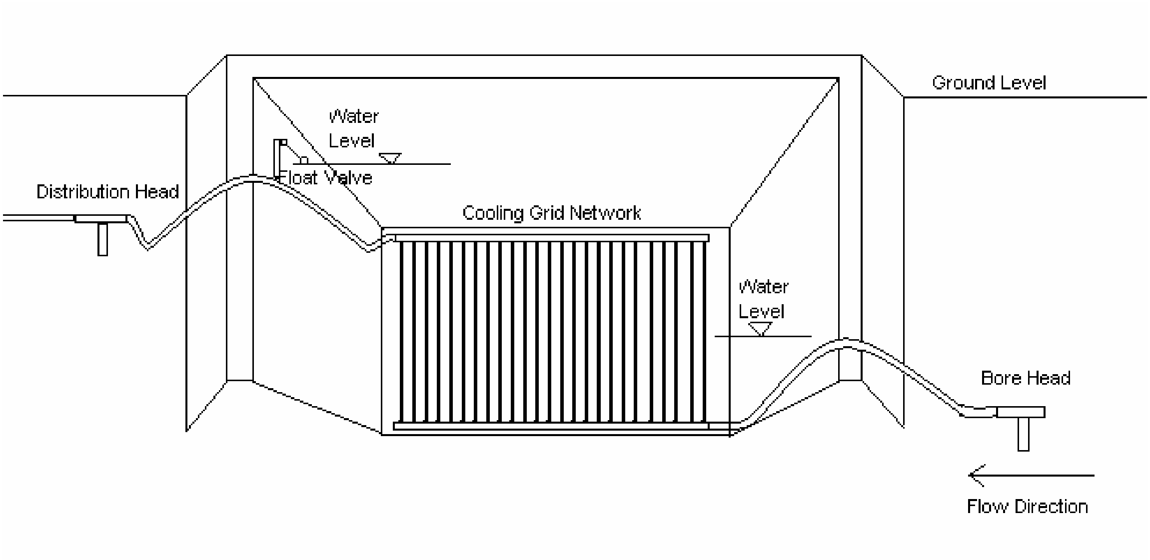

Figure 1.1 Schematic of Typical Cooling Grid

Currently each individual cooling grid is designed and sized using a spreadsheet design model according to the individual bore temperature and discharge characteristics to guarantee the required outlet temperature at the maximum flowrate of the system. The design model utilises a number of variables, constants, and theoretical calculations to determine the length of pipe that is required for the desired amount of heat to be transferred from the hot artesian water into the cooling pond.

This project is aimed at analysing this design model to determine its accuracy in designing each cooling grid as well as investigating the possible alternative pipe materials that may be used within each grid to minimise costs whilst maintaining the desired heat transfer.

The principal aims of this project are to predict and confirm the heat transfer parameters for cooling grids submerged in water ponds used for cooling artesian groundwater, investigate other available cooling options and validate/modify parameters within the existing design model to more accurately reflect existing operation.

The specific objectives of the project are as follows:

1. Research material properties of alternate pipe materials, heat transfer mechanisms through air and water, alternative cooling techniques, flow characteristics and associated hydraulics theory for pipe networks.

2. Undertake sensitivity analysis of the spreadsheet design model to verify important variables to aid in pipe material selection.

3. Design a cooling grid test setup for on-site use and an experimental procedure to compare its performance using differing pipe materials to theoretical calculations from the existing spreadsheet design, test in field to compare the heat transfer characteristics in air and water using the selected pipe materials.

4. Comparatively analyse designs tested accounting for costs, material availability, flow characteristics at different flow rates, cooling performance and maintenance requirements.

5. Validate and calibrate the current DNR&W design spreadsheet using measured data, and make recommendations.

6. Write a dissertation and submit by 30/10/2008

By undertaking the necessary research and testing the project will allow increased accuracy when designing cooling grid systems whilst ensuring the efficient use of resources by the DNR&W.

CHAPTER 2

BACKGROUND

2.0 Background

2.1 The Great Artesian Basin

The Great Artesian Basin (GAB) is one of the largest artesian groundwater basins in the world. It underlies approximately one-fifth of Australia and extends beneath arid and semi-arid regions of Queensland, New South Wales, South Australia and the Northern Territory, as shown in Figure 2.1. The GAB covers a total area of over 1 711 000 square kilometres and has an estimated total water storage of 64 900 million megalitres.

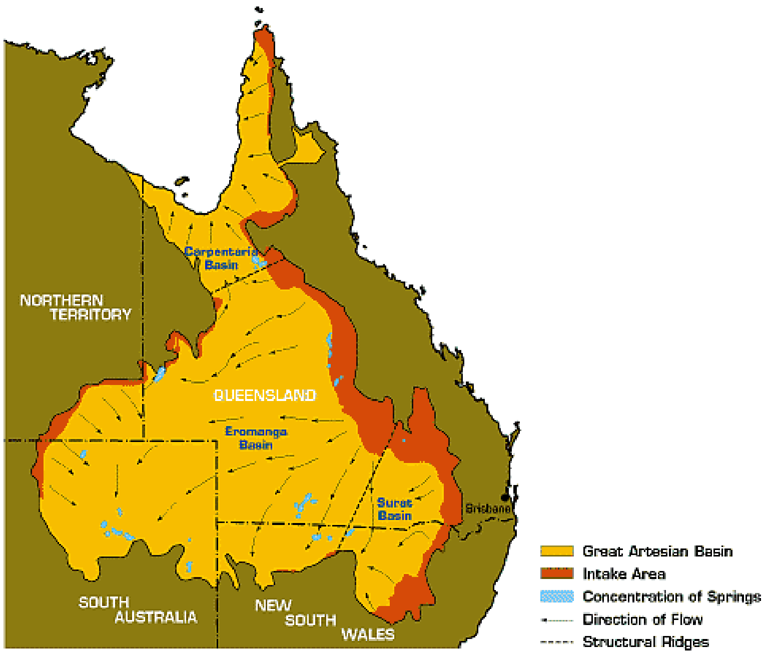

Figure 2.1: Map of Great Artesian Basin, *Source: NR&W Qld.*

The Great Artesian Basin consists of alternating layers of permeable sandstone aquifers and impermeable siltstones and mudstones. The depth of these layers varies from less than 100 metres at the Basin boundaries to over 3 000 metres in the deeper parts of the Basin. The rate at which water flows through the sandstones varies between one and five metres per year. Water enters the Basin by infiltration of rainfall into the outcropping sandstone aquifers mainly along the western slopes of the Great Dividing Range. This infiltration and flow pressurizes the water between the permeable and impermeable layers. Pressurised groundwater is then discharged via approximately 10 000 bores within the Basin and also naturally from artesian springs in the south-western area because the potentiometric surface is above ground level (see Figure 2.2).

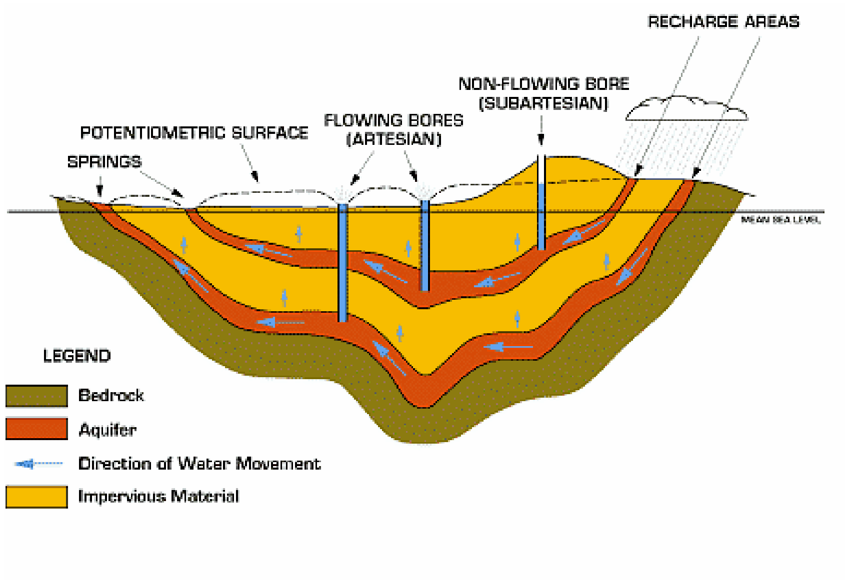

Figure 2.2: Great Artesian Basin Formation, *Source: NR&W Qld.*

Water temperatures vary from 30˚C in the shallower areas to up to 99˚C in the deeper areas. Heating of the water occurs naturally because of its proximity to the Earth's hot mantle.

2.2 Water Usage in the Great Artesian Basin

Prior to human development of the Basin, it is estimated that approximately 300 Megalitres/day of water entered the permeable aquifers of the Great Artesian Basin in Queensland. All of this inflow, as well as the recharge from other states, discharged as surface springs, or leakage through the ground surface. In this way a natural equilibrium of inflow to outflow was maintained.

Europeans first discovered the artesian groundwater of the Great Artesian Basin in 1878 when a shallow bore sunk near Bourke in New South Wales produced flowing water. A bore is simply a deep hole lined with a metal casing which usually ranges in diameter from 100 to 300 millimetres. Many bores were soon drilled throughout the Basin in north-west New South Wales and north-east South Australia. The first flowing artesian bore in Queensland was drilled in 1887 near Cunnamulla. Following this discovery, over 500 bores were sunk over the next decade and by 1915 a total of 1500 bores were supplying an approximate discharge of 2000 Megalitres/day of uncontrolled artesian water to Queensland properties.

This seemingly endless supply of water allowed the development of extensive grazing country throughout the grass plains of western Queensland. Thousands of kilometres of bore drains were excavated to transport water throughout the properties. Bore drains are shallow earth trenches which are excavated to allow the water to travel across the ground surface. However, this increased outflow of water from the Basin resulted in significant pressure losses with up to a third of all bores now requiring pumps to bring the water to the surface. Regulations were introduced to all new bores in 1954, stating that all bores must have a control valve in place and use pipelines to distribute the water other than open drains. These measures, along with the encouraged piping of older bores, have resulted in a gradual return to equilibrium between recharge and discharge throughout the Basin today.

2.3 Environmental Impacts

Artesian water, being easy and inexpensive to utilise, is often used inefficiently after it reaches the surface. In many areas, artesian water is traditionally flowing uncontrolled from bores into open drains and creeks for stock to drink with nearly 14 000 km of bore drains currently in use throughout Queensland alone. Even in well-maintained drains, up to 97 per cent of the water is lost through evaporation and seepage.

This ineffective and inefficient method of water transport results in serious environmental impacts and land degradation issues (see Figure 2.3). Some of the impacts include:

- Feral animals are provided with a habitat and permanent water supply
- Infestations of invasive woody weeds, such as prickly acacia, in and around bore drains
- Erosion problems often result from drains overtopping or breaking their banks
- Salinity problems can be created or aggravated
- Bore drains built across a slope catch run off water, reducing rainfall infiltration below drains and thereby limiting pasture growth
- Concentration of minerals by evaporation (e.g. Sodium and Fluoride) can negatively affect animal health or induce scalding on the soil surface
- Amount of time, expense and labour required to maintain bore drains.


EROSION FERAL ANIMALS


SALINITY SCALDING

Figure 2.3 Environmental Problems with Bore Drains, *Source: DNR&W*

2.4 The Great Artesian Basin Sustainability Initiative

The Great Artesian Basin Sustainability Initiative (GABSI) is a joint Federal and State government project designed for the continued sustainability of the vast hidden artesian water resource that is the Great Artesian Basin. GABSI's role is to work in conjunction with landholders to rehabilitate uncontrolled bores drilled prior to 1954, and replace bore drains with pipelines delivering the water to tanks and troughs at designated watering points.

Figure 2.4 Controlled Bore Piped to Tanks, *Source: DNR&W*

To rehabilitate an uncontrolled bore, the bore and its casing are tested using geophysical logging probes and a dye test to determine the casing condition, size and strata details. This information is then used to determine the correct method of rehabilitation. The rehabilitation method may include some basic repairs to the bore casing near ground level and new headworks, relining of the bore casing by inserting a smaller diameter pipe into the bore and cementing the annulus between the two casings, or by plugging the entire bore with concrete to stop flow and drilling a new bore nearby using inert casing.

Once the bore has been successfully rehabilitated, the water is piped throughout the areas which the bore drains were previously servicing to new designated watering points. Each watering point's location and size is designed to;

- hold at least 2 days supply of water for the stock in the area,
- maintain a maximum walking distance between watering points of 1.5 kilometres for sheep and 2 kilometres for cattle,
- minimise the opportunity for feral animals by using specifically designed high sided troughs and,
- reduce erosion by installing concrete aprons around all watering points.

By capping and piping the artesian bores farm management becomes easier, productivity increases whilst water is conserved. Other benefits include the reduction of feral animal habitat, reduced maintenance time, stock weakened by drought are better able to drink from troughs, the water quality in these piped systems is considerably better at the watering point when compared to that using bore drains and when a number of properties are serviced by one bore all properties, including the ones farthest from the supply are guaranteed water.

A well designed system allows the effective use of the whole property all year round with pipeline systems that can deliver water to parts of the property that previously could not be reached by bore drains. Spear traps, which allow animals to enter safely but not to exit, can be installed at watering points so stock can self muster and managers can ensure more effective spelling of paddocks as watering points are turned off. Also, it is possible to deliver food supplements and medication to stock through drinking water reducing travel and labour costs.

2.5 Cooling Grids

Artesian water can reach very high temperatures because of the naturally high temperatures at large depths near the earth's mantle. The temperature of the water throughout the GAB ranges from 30˚C up to 99˚C at depth. The high temperature of the water is not of concern when it is flowing uncontrolled into bore drains, however when the water is piped the temperature presents a problem in terms of polyethylene pipe degradation.

The medium density polyethylene (PE 80B) pipe that is used for piping the artesian water throughout the GAB requires a temperature below 45℃ to maintain a design lifespan of greater than 50 years (James Hardie Pipelines, 1997). At higher temperatures the PE 80B pipe will only remain viable for 25 years or less because of the heat deterioration of the pipeline. Hence, the water must be cooled before entering the reticulation system.

The current practice used to cool artesian water utilises the natural pressure of the bore to pump the hot water through a network of 19.1mm plain walled copper pipes submerged in an earthen walled pond at a depth of 2 metres (see Figure 2.5). The copper pipes are arranged in parallel which are fed and collected by 100 mm copper manifolds at either end (see Figure 2.6). Each copper grid is sized according to the individual bore characteristics of pressure, temperature, and maximum flowrate using a spreadsheet model which will be discussed later.

At present, the cooling grid design model spreadsheet that is used to size each grid in each scheme is relatively untested. There is a need to validate this design model to ensure the correct sizing of grids for sustainable resource management and to ensure that the theoretical calculations are truly representative of in field results. This study will focus on the theoretical versus practical performance of the model and investigate any optimisations which may be possible.

Figure 2.5 Installed Cooling Grid, *Source: DNR&W*

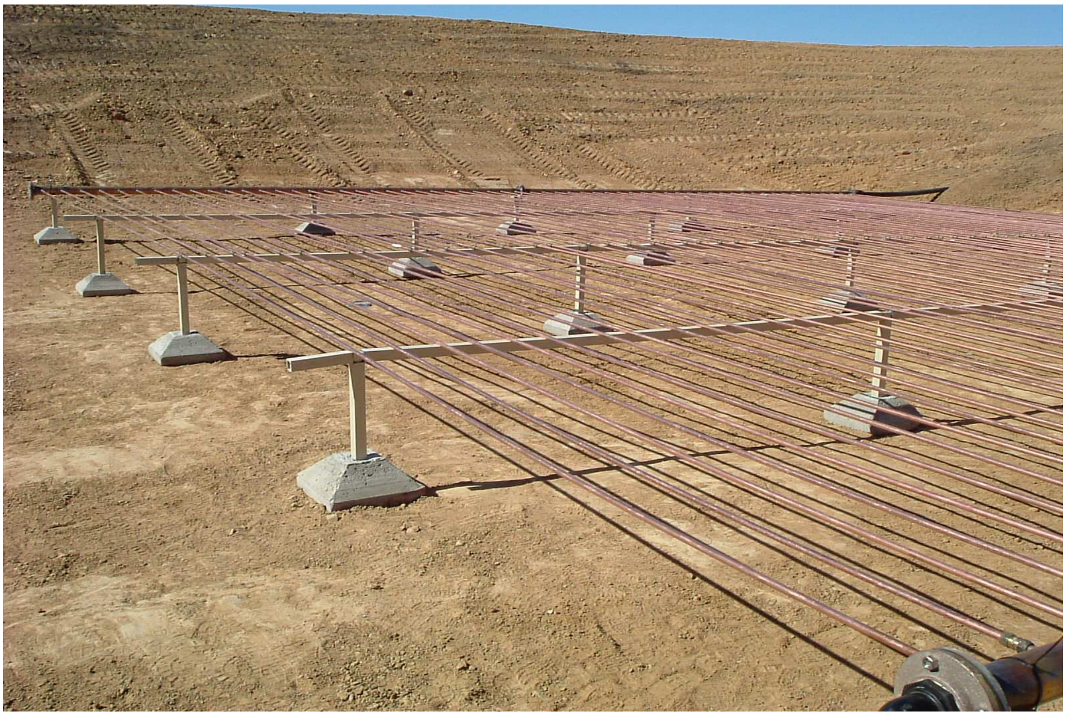

Figure 2.6 Installed Cooling Grid, *Source: DNR&W*

CHAPTER 3

LITERATURE REVIEW

3.0 Literature Review

This chapter will review literature on previous work to expand upon the material outlined in previous sections whilst providing a context for this project. A review of the physical heat transfer principles and alternative cooling practices will follow to provide an increased understanding of the subject.

3.1 Review of Previous Work

Copper cooling grids are a relatively new cooling method for artesian water and have only been in use for less than a decade. Water running uncontrolled into drains required no cooling as it was exposed to convective and evaporative cooling effects. Prior to the use of copper grids piped artesian water was cooled using steel or polyethylene pipe submerged in an earthen walled dam. This system utilised little to no design process. The steel or polyethylene would simply be replaced as necessary. Some piped schemes employed no cooling technique at all which rapidly deteriorated the polyethylene pipe requiring regular maintenance.

Since the copper cooling grids have been utilised by the Department of Natural Resources and Water many changes to their design have occurred. It was thought by the GABSI staff that by using copper pipe with a ‘crinkled’ or ‘finned’ surface the heat transfer into the pond would be greater because of the increased surface area of the pipe. Over time this practice was deemed unreliable as the finned pipe allowed for considerable algal growth requiring frequent cleaning to maintain the desired heat transfer capacity. This algal growth was factored into the design for a period by adding an extra 50% to the size of each grid to account for the poor performance and loss of heat transfer. The choice of pipe was converted back to plain walled copper pipes in both the design and installation of systems.

The design model used in the creation of copper cooling grids has also been subject to change over time and has come under review in previous studies. As the model has developed and been added to over time, a broader scope of calculations has been included allowing for increased accuracy in design.

It is important to note the above continued changes to cooling grids and their design to understand the previous studies undertaken and set the context in which they were produced.

Martin (2003) analysed the practical versus theoretical performance of finned copper cooling grids and developed a design spreadsheet to account for any inaccuracies. Martin (2003) tested the theory on two separate bores using varied flowrates over a period of time. The flow control valve used in their experiments significantly affected the pressure in the system inducing a 2 to 3 metre head loss through the valve. In addition to the experiments performed, Martin (2003) also evaluated the possibility of modifying current practice by employing different materials. No practical or theoretical testing was conducted and only cooling towers and stainless steel as an alternative pipe material in the grid were mentioned.

Martin (2003) states that…

> "stainless steel does not offer the heat transfer capabilities of copper so a larger grid is required…the anaerobic environment in a cooling pond would not allow the protective oxide film to develop and therefore you would not expect stainless steel to stand up to corrosion better than normal steel…it is also more expensive."

These claims were examined during this project's research and testing.

Martin (2003) reports that cooling towers offer no substantial benefit to the cooling of piped artesian water in Queensland because of the loss of natural bore pressure and requirement of power for pumping. Martin (2003) confirmed Eigland (2000) which is a report for the 'Capping and Piping the Bore Program' in New South Wales by the Department of Land and Water Conservation. The schemes are designed in Queensland to utilise the natural bore pressure and flow so as to remove the power requirement for pumping.

Webb (2002) evaluated the performance of the addition of heat dissipating fins to the cooling grid pipes as well as varied pipe wall thicknesses. These heat dissipating fins were proven to be impractical during installation. Webb (2002) also analysed the performance of the grids without any cost evaluation giving no real world validation of the 'improved' design. The fins also promoted increased external algal growth inhibiting the overall heat transfer and introducing the requirement of manual cleaning of the pipe exteriors.

An internal report conducted by Alsemgeest and Zuino (2002) for the Department of Natural Resources and Water evaluated the necessity of cooling grids altogether. The report investigated the effects of piping the water claiming the increased pressure from piping would reduce the bore temperature enough to allow for a sacrificial length of polyethylene pipe to be used close to the bore to provide an area for cooling. The difficulty in prediction of the length of sacrificial pipe required presented a problem as well as the prediction of temperature decrease from pressure recovery. PEX polyethylene pipe is a new pipe designed to withstand temperatures up to 80℃. This PEX pipe may become a viable option for an extended length from the bore head to allow for cooling as its price decreases with continued usage. This pipe is currently in use by GABSI to connect the bore head to the cooling grid although it is still relatively expensive for the short connection distance. The result of the Alsemgeest and Zuino (2002) report certainly presents an area of further study when the price of PEX pipe reduces.

Watt (2007) analysed the theoretical performance of varied cooling grid pipe sizes and grid configurations. The report used the current design model to investigate the performance of cooling grids with larger and smaller pipes as well as having a 'stacked' grid with one set of pipes above another. Cost, performance, maintenance requirements and ease of installation were considered as criteria for optimisation which yielded a recommendation of a 31.8mm pipe size for the current grid and a 38.1mm pipe size for a 'stacked' design. Although real world costs were involved no practical testing was conducted which assumed the design model reflected actual performance. Watt (2007) indicated the necessity of cooling grid performance evaluation to optimise design.

It is still unknown whether the current design model accurately represents in situ results which are the main focus of this project. As a result of previous investigations there is a need to validate the design model to analyse how the previous findings have been used to alter the current model. At this point in time, NR&W do not have confidence that the existing cooling grid design model satisfactorily replicates the cooling grid's performance in a practical situation.

3.2 Heat Transfer Mechanisms

Heat transfer is defined as the energy transferred when a temperature gradient exists within a system, or whenever two systems at different temperatures are brought into contact (Kreith & Bohn, 2001). The physics of heat and heat transfer are well known but are included here in a brief review on the subject.

There are three main modes of heat transfer. They are conduction, convection and radiation. Each of these will be discussed in-turn.

3.2.1 Conduction

Conduction of heat occurs in gases, liquids and solids and is assumed to involve no bulk motion. Heat is transferred from rapidly moving high energy molecules which randomly collide with low energy slow moving molecules in a fluid where a temperature gradient exists (Janna, 2000). These random collisions exchange momentum and energy and therefore heat. It is possible to quantify the amount of heat transferred per unit of time through the mode of conduction using Fourier's Law of Heat Conduction, equation 3.11 (Incropera & DeWitt, 1996).

$$\begin{aligned} q &= -k\frac{T_1 - T_2}{L} \\ \Rightarrow q &= k\frac{\Delta T}{L} \end{aligned} \tag{3.11}$$

where q = heat flux perpendicular to direction of transfer [W/m^2];
k = thermal conductivity [W/m.K];
L = length [m]; and
T = temperature [°K].

3.2.2 Convection

Convection of heat through liquids is comprised of two mechanisms. Heat is transferred by random molecule collisions as outlined above as well as by the bulk motion within the fluid (Incropera & DeWitt, 1996). Heat transfer by convection can be forced or natural, or free, in nature. Forced convection occurs when an external force such as an agitator or pump creates the fluid motion which will transfer heat between areas of higher temperature and lower temperature. In contrast, natural or free convection occurs from the buoyancy forces which are created by the density differences between areas of higher temperature and lower temperature (Kreith & Bohn, 2001).

In both forced and free convection the heat flux created can be quantified using Newton's Law of Cooling, equation 3.12 (Incropera & DeWitt, 1996).

$$q = h(T_1 - T_2) \qquad (3.12)$$

.

where q = heat flux perpendicular to the direction of transfer [W/m^2];
h = convection heat transfer coefficient [$W/m^2.K$]; and
T = temperature [°K].

This law utilises a proportionality constant, *h* [W/m^2 .K], known as the convection heat transfer coefficient. Some typical values are shown below in Table 3.1.

Table 3.1 Typical values of the convection heat transfer coefficient (Incropera & DeWitt, 1996).

Process	***h*** **(W/m²$^{}$.K)**
Free Convection	
Gases	2 – 25
Liquids	50 – 1000
Forced Convection	
Gases	25 – 250
Liquids	50 – 20000

It is also important to note that if a temperature gradient exists between a fixed surface and a free fluid a consequence is the development of a region in the free fluid where the bulk velocity varies from zero at the surface to a finite value associated with the relative conditions. This is because of the viscous forces within the fluid and is referred to as thermal boundary layer development which will vary from system to system (Kreith & Bohn, 2001).

3.2.3 Radiation

Radiation or thermal radiation is the energy emitted by a body by virtue of its temperature and at the expense of its internal energy. Radiation needs no transport medium and is most efficient in a vacuum (Incropera & DeWitt, 1996). All heated solids, liquids and some gases emit thermal radiation to their surroundings. This heat flux can be quantified using equation 3.13 if both the surroundings and the emitter are blackbodies (Incropera & DeWitt, 1996).

$$q = Ah(T_1 - T_2)$$
$$where \Rightarrow h = \varepsilon\sigma(T_1 + T_2)(T_1^2 + T_2^2) \qquad (3.13)$$

where q = heat flux perpendicular to the direction of transfer [W];
h = radiation heat transfer coefficient [$W/m^2.K$];
A = surface area [m^2];
ε = emissivity [dimensionless];
σ = Stefan-Boltzmann constant [5.67×10^{-8} $W/m^2.K^4$];
T_1 = surface temperature [°K]; and
T_2 = surrounding temperature [°K];

3.2.4 Heat Transfer in Cooling Grids

All three heat transfer mechanisms contribute to heat loss through cooling grids. Heat energy is conducted through the metal pipes into the pond. Free convection occurs within the pond as the temperature difference between the pipes and the pond creates a buoyancy effect from density changes resulting in convection currents throughout the pond. Heat is also radiated from the hot bore water through the pipe and into the pond.

Solar radiation is of great importance as well because of its contribution to heat loss. As solar radiation strikes the surface of the cooling pond it contributes to the evaporation of water molecules. This evaporation requires a large input of energy from the molecule’s surroundings as it changes phase from liquid to gas. This energy comes partly from solar radiation but mainly from the surrounding water molecules, hence cooling the water in the pond. This is known as the evaporative cooling effect (Allen *et al*, 1998). Ambient temperature and windspeed are also significant contributors.

Cooling grids are designed to provide the appropriate amount of heat transfer for the system's maximum designed flowrate, which occurs as the pipeline system is filled. After the initial 'filling' of the pipe, tank and trough system the actual operating flowrate is considerably reduced. The flowrate required to maintain this level is dependent upon the stock drinking requirements, losses due to pipe leakage and evaporation from the troughs. This means that over 99% of the system's working life will be at a flowrate considerably less than that required at fill.

3.3 Cooling Grid Design Spreadsheet

A Microsoft Office Excel spreadsheet has been developed by NR&W using worked examples from the *POLIPLEX Polyethylene Pipe Design Textbook*, 1997 from James Hardie Plumbing and Pipelines Pty Ltd, Australia. The spreadsheet is used to calculate the length of pipe required in the grid to reduce the temperature of the water in the pipe to the required outlet temperature of below 45 ℃, the number of pipes required in the grid using a predetermined individual pipe length as well as the friction loss through the grid.

The user inputs are of peak flow rate, inlet temperature, pressure head at inlet and the length of individual pipe between the manifolds. The spreadsheet model will be discussed further in Chapter 4.

3.4 Alternative Water Cooling Practices

There are many ways in which water can be cooled. However the method chosen is dependent upon the individual cooling purpose, cost, infrastructure, power availability and design efficiency to name a few. Some commonly used water cooling practices include gas refrigeration, cooling tanks/towers, passive radiator cooling systems and heat pipes. These alternative water cooling techniques to cooling grids will be discussed to outline any possible applications to the GABSI schemes.

3.4.1 Gas Refrigeration

Gas refrigeration involves a process which utilises the heat changes as a substance is evaporated and condensed continuously throughout a system of pipes as shown in Figure 3.1.

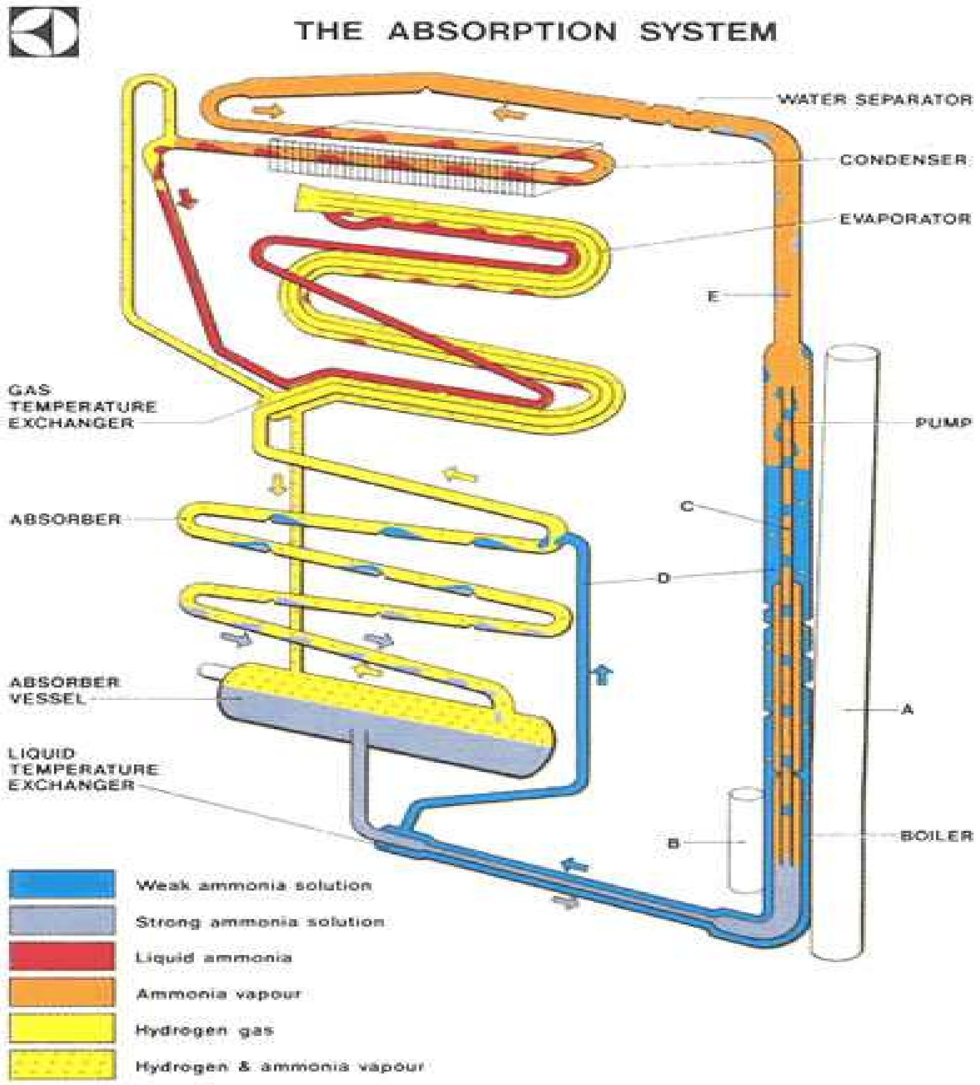

Figure 3.1 Gas Absorption System. *Source: Lehman's Gas Refrigerators, 2007*

This continuous absorption system has no moving parts, absorbs heat efficiently and requires minimal maintenance. However, a supply of heat either from electricity, gas or kerosene is required to drive the system. Put simply, liquid ammonia is passed through a network of tubes called the evaporator, the ammonia then vaporises because of a change in pressure caused by the introduction of hydrogen gas. This draws heat from the surrounding environment. The ammonia gas is then mixed with water to separate it from the surrounding hydrogen and then boiled to extract the pure ammonia gas. This gas is then condensed in a heat exchanger to form liquid ammonia and the process begins again (Lehman's Gas Refrigerators, 2007).

3.4.2 Cooling Tanks/Towers

Cooling towers are used in the many industries to dissipate waste heat to the atmosphere through the cooling of a water stream to a lower temperature. This cooling technique employs the evaporative cooling effect where a small amount of the water is allowed to evaporate to provide cooling to the rest of the water stream (Cooling Technology Institute, 2007). The heat energy from the water stream is transferred to the surrounding air increasing its temperature and relative humidity. This heated air is then released to the atmosphere and replaced with cooler ambient air through inlets at the base of the tower using the forces of convection.

Cooling tanks are simply water holding tanks which give the heated water time to cool. These tanks also utilise the evaporative cooling effect to remove the majority of the heat energy to the atmosphere. Cooling tanks can be situated on the ground surface or raised off the ground to take advantage of gravitational forces for cool water delivery.

3.4.3 Passive Radiator Cooling Systems

Another cooling technique which utilises the convection mode of heat transfer is passive radiators. Passive radiators consist of a network of metal fins or pipes similar to that used in car radiators. These fins are filled with the water to be cooled and subjected to free and forced heat convection in a natural outdoor environment. The heat is transferred through the fins through the mode of conduction and removed to the atmosphere by the mode of convection. To maintain optimum conditions passive radiator cooling systems should be shaded from sunlight to maintain the maximum possible temperature gradient between the heated water and the atmosphere and prevent solar radiation interference.

3.4.4 Heat Pipes

A heat pipe is simply a pipe that can quickly and efficiently transport heat from one area to another. They are often referred to as superconductors of heat because of their extraordinary heat transfer capabilities (CheResources, 2008). Heat pipes consist of a sealed copper or aluminium tube. Within this tube the inner surface is lined with a wick-like structure which allows for the transportation of a liquid or working fluid. The working fluid is usually liquid ammonia which evaporates from the wick when subjected to heat and travels through the hollow centre of the tube in gaseous form. If the heat pipe is subjected to a hot and cool environment on either end, the ammonia gas will then condense at the cool end and be absorbed back into the wick. The ammonia liquid then travels back to the hot end through the wick due to gravitational forces, if the pipe has a vertical orientation as well as by the flux created by the evaporating ammonia at the other end (Chisholm, 1971). A sample heat pipe is shown in Figure 3.2.

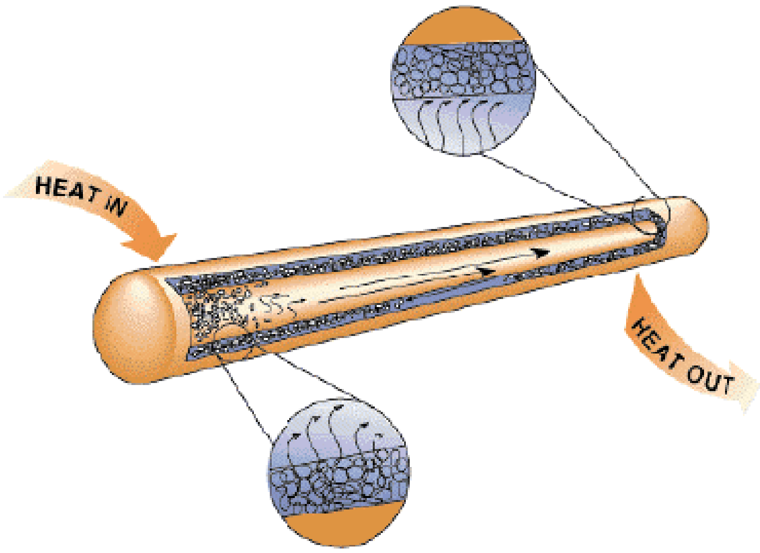

Figure 3.2 Heat Pipe *Source: CheResources, 2008*

Heat pipes are used in a wide range of cooling applications including laptops, refrigeration, air-conditioning, heat exchangers and in space technology.

3.4.5 Applications to Artesian Bore Water Cooling

Gas refrigeration is a minimal maintenance self sufficient system which requires only one input of heat. It presents as a possible alternative for some artesian bore water cooling systems if the heat of the bore could be used as this heat source. The temperature of the bore would need to be higher than that of the boiling point of the hydrous ammonia. The relative size is a limiting factor and the system's ability to handle high flowrates may present as a problem which would require significant development if this process was chosen as an alternative.

Cooling towers require the use of some of the water stream for cooling. Artesian bore piping schemes require the system to be fully enclosed to maintain the natural pressure of the bore to remove the need for powered pumping, therefore cooling towers may not be a viable option for this type of water cooling. Cooling tanks however, are able to utilise gravity for the system's pressure requirements. This may prove effective in the Queensland artesian bore piping schemes where the terrain is mostly flat and the bore pressure is sufficient to reach an elevated tank. Cooling tanks are used in conjunction with powered pumps in most New South Wales piping schemes.

Passive radiator cooling systems can maintain the bore pressure, are relatively cheap and open up the possibility of recycling used radiators. However, as air has a low heat transfer capacity a larger surface area for cooling would be required. Increased development of this passive cooling technique may increase its potential for its application in artesian water cooling systems.

Heat pipes, although relatively more expensive than other cooling techniques, require little to no maintenance, are fully self sufficient and depend on the physics of the working fluid. Applications of this technology to the cooling of artesian bore water would require significant research and design to extract the heat energy from the water and dissipate it to the environment whilst maintaining the natural pressure of the bore.

The above systems all require fewer earthworks than the current cooling grid system which would reduce costs and maintenance requirements. Further investigation into one or all of these systems may be viable in the future but was not the subject of this investigation.

3.5 Flow Characteristics in Pipelines

As the velocity of fluid flowing within pipelines change, the physical characteristics of the flow profile also vary. At smaller velocities water particles flowing in pipelines are observed to move in straight lines which slide over one another with little to no mixing occurring within the fluid. The fluid appears to move by the sliding of laminations of miniscule thickness over adjacent layers (Finnemore & Franzini, 2002). Hence, this type of flow is labelled laminar flow.

As the velocity within a pipeline increases, the paths of the water molecules become more varied. A period of transition is observed in which the water particle movement may become wavy with no definite wave frequency and with a small amount of particle mixing. Following this transition period turbulent flow is observed. Turbulent flow is characterised by the irregular motion of a large number of water particles with no observable pattern during a small time interval (Finnemore & Franzini, 2002).

The type of fluid flow can be easily determined when the flow parameters are known using Reynold’s number. Reynold’s number is simply a ratio of inertia forces to viscous forces and assumes no gravitational or capillary action in a completely filled pipeline (Finnemore & Franzini, 2002). Reynold’s number values of between 0 and 2000 are identified as laminar flows, values of between 2000 and 4000 identify the transition period of flows and values of above 4000 are categorised as turbulent flows. Reynolds number can be calculated using equation 3.5 (Finnemore & Franzini, 2002).

$$R_e = \frac{VD}{\nu} \tag{3.5}$$

where R_e = Reynold's number [dimensionless];
V = flow velocity [m/s];
D = pipe diameter [m]; and
v = kinematic viscosity of fluid [m^2/s].

3.6 Pipe Material Selection

In order to identify improvement in the cooling grid design differing pipe materials need to be analysed to ensure continuity in the model as well as to optimise the overall design. Pipe material selection is important because of availability, cost, maintenance requirements, application suitability, heat transfer parameters and ease of installation.

To maintain good experimental design copper was chosen as the control material. Copper is the pipe material of choice at present and the design model was created for this metal. Copper has been used in the design of cooling grids because of it's availability in the correct diameter, excellent heat transfer abilities and resistance to corrosion (Janna, 2000).

Aluminium was the second choice for pipe material. Aluminium is similar to copper in that it is low cost, offers good heat transfer capacity, good workability and resistance to corrosion with the formation of an aluminium oxide film to resist oxidation (Janna, 2000). The third choice for pipe material was stainless steel. Stainless steel was chosen to provide a comparison in heat transfer capacity having a thermal conductivity of 22 times less than that of copper (see Table 3.5).

Stainless steel is also relatively low cost and has good availability in the correct diameter. A chromium oxide film is present on stainless steel when exposed to oxygen which provides rust protection (Janna, 2000). Martin (2003) also discounted stainless steel as a possible alternative, as outlined in Section 3.1, so the material is included here to prove or disprove Martin (2003).

Table 3.5 Thermal conductivity of some materials. *Source: Janna, 2000*

Material	**Thermal Conductivity, *k* (W/m.K)**	**Commercial cost per metre ($)**
Aluminium	240	8.30
Copper	380	14.30
Polyethylene	0.45	2.64
PEX pipe	0.38	5.00
Stainless Steel	17	15.80

The spreadsheet model will now be discussed in detail to provide an understanding of the model itself, the sub-models and hydraulic equations used. A sensitivity analysis of the model will be discussed to identify important variables and areas for possible improvements or modifications.

CHAPTER 4

MODEL DESCRIPTION & SENSITIVITY ANALYSIS

4.0 Model Description and Sensitivity Analysis

The spreadsheet model developed by Andrew Brier for NR&W utilises worked examples from the *POLIPLEX Polyethylene Pipe Design Textbook*, 1997 from James Hardie Plumbing and Pipelines Pty Ltd, Australia to determine the correct cooling grid size for each individual GABSI scheme.

User inputs and defined constants are used to calculate the convection heat transfer coefficients for forced convection in the cooling grid pipes and natural convection in the cooling pond. These heat transfer coefficients are then used to calculate the overall heat transfer coefficient for the entire system. The amount of heat required to be transferred to the pond can then be determined.

Temperature gradients, pipe radii and material properties are then used to calculate the area of pipe material, and therefore the pipe length, required to transport this heat. The frictional head loss through the grid is also calculated.

4.1 Model Calculations

The model is complex and interactive with values taken from graphs and trials being calculated to determine the correct grid size. The user inputs, defined constants and equations 4.1 to 4.25 are outlined below to illustrate the processes within the spreadsheet model.

4.1.1 User Inputs

Peak Water Demand (L/s)	-	Q
Inlet / Bore Temperature (°C)	-	T_i
Pressure Head at Inlet (m head)	-	P
Length of Individual Pipe (m)	-	L_2
Required Outlet Temperature (°C)	-	T_o
Water Temperature of Pond (°C)	-	T_p
Inside Diameter of Pipe (m)	-	D_i
Outside Diameter of Pipe (m)	-	D_o

4.1.2 Defined Constants

Specific Heat of Water

$$C_w = 4180 \text{ J / kg . °C}$$

Conduction Coefficient for Pipe Material

$$K_c = 380 \text{ W / m . °C}$$

Conduction Coefficient for Water

$$K_w = 0.56 \text{ W / m . °C}$$

Density of Water

$$\rho = 990 \text{ kg / m}^3$$

Kinematic Viscosity of Water (calculated from graph)

$$v = 0.000000500 \text{ m}^2 / \text{s}$$

Fouling Factor for Water (>50˚C)

$$R_f = 0.0 \text{ m}^2 . \text{°C} / \text{W}$$

Coefficient of Roughness

$$k = 0.000003 \text{ m}$$

Pi

$$\pi = 3.14159\ldots \text{ dimensionless}$$

4.1.3 Calculations

Average Temperature in Grid – T_a (°C)

$$Ta = \frac{(Ti + To)}{2} \tag{4.1}$$

Inside Radius of Pipe – r_i (m)

$$r_i = \frac{D_i}{2} \tag{4.2}$$

Outside Radius of Pipe – r_o (m)

$$r_o = \frac{D_o}{2} \tag{4.3}$$

Left Fluid Temperature Difference – ΔT_a (℃)

$$\Delta Ta = Ti - Tp \tag{4.4}$$

Right Fluid Temperature Difference – ΔT_b (℃)

$$\Delta Tb = To - Tp \tag{4.5}$$

Log – Mean Temperature Difference – ΔT_{LM} (℃)

$$\Delta T_{LM} = \frac{\Delta Tb - \Delta Ta}{\ln(\Delta Tb / \Delta Ta)} \tag{4.6}$$

Correction Factor – F (dimensionless)

Calculated from graph

Mean Temperature Difference – ΔT_{MEAN} (℃)

$$\Delta T_{MEAN} = \Delta T_{LH} * F \tag{4.7}$$

Velocity in Pipes – V (m / s)

$$V = \frac{\left(\frac{(Q/1000)}{(\pi * (Di^2)/4)}\right)}{n} \tag{4.8}$$

Reynold's Number in Pipes – *Re* (dimensionless)

$$\mathrm{Re} = \frac{(Di * V)}{\nu} \qquad (4.9)$$

Prandtl Number in Pipes – *Pr* (dimensionless)

$$\mathrm{Pr} = \frac{(Cw * \rho * \nu)}{Kw} \qquad (4.10)$$

Nusselt Number in Pipes – *Nu* (dimensionless)

$$Nu = 0.023 * \mathrm{Re}^{0.8} * \mathrm{Pr}^{0.4} \qquad (4.11)$$

Heat Transfer Coefficient in Flowing Water – h_1 (W / m^2 . ℃)

$$h_1 = \frac{(Nu * Kw)}{Di} \qquad (4.12)$$

Mean Temperature for Natural Convection in Pond – T_m (℃)

$$Tm = \frac{(Ta + Tp)}{2} \qquad (4.13)$$

Kinematic Viscosity for Natural Convection – *v* (m^2 / s)

Calculated from graph and T_m

Volume coefficient of Expansion for Water – *B* (m^3 / ℃)

Calculated from graph and T_m

Grashof Number – *Gr* (dimensionless)

$$Gr = \frac{(g * \beta * (Ta - Tp) * Do^3)}{\nu^2} \tag{4.14}$$

Rayfield Number – *Ra* (dimensionless)

$$Ra = Gr * \Pr \tag{4.15}$$

C (dimensionless) Calculated from graph and *Ra*

n (dimensionless) Calculated from graph and *Ra*

Nusselt Number for Natural Convection in Pond – Nu_1 (dimensionless)

$$Nu_1 = C * Ra^n \tag{4.16}$$

Heat Transfer Coefficient in Still Water – h_s (W / m^2 . ℃)

$$h_s = \frac{(Nu_1 * Kw)}{Do} \tag{4.17}$$

Modified Coefficient for Algal Growth – h_2 (W / m^2 . ℃)

$$h_2 = 0.60 * h_s \tag{4.18}$$

Heat required to be transferred to pond – *q* (W)

$$q = Q * Cw * \rho * (Ti - To) \tag{4.19}$$

Overall Heat Transfer Coefficient – *U* (W / m^2 . °C)

$$U = \frac{1}{\left[(\frac{1}{h_1}) + Rf + (\frac{r_i}{Kc}) * \ln(\frac{r_o}{r_i}) + \left((\frac{r_i}{r_o}) * Rf) + (\frac{r_i}{r_o * h_2}) \right) \right]} \tag{4.20}$$

Area of Pipe Required – *A* (m^2)

$$A = \frac{q}{(U * \Delta T_{MEAN})} \tag{4.21}$$

Total Length of Pipe Required – *L* (m)

$$L = \frac{A}{(\pi * Di)} \tag{4.22}$$

Pipe Friction Factor – *f* (dimensionless)

$$f = 0.0055 \left[1 + \left(\frac{(20000 * k)}{Di} + \frac{106}{\text{Re}} \right) 0.33 \right] \tag{4.23}$$

Frictional Loss through Pipes – *hf* (m head)

$$hf = \left(\frac{(f * L_2 * v^2)}{(2 * g * Di)} \right) * \left(1 + \frac{20}{100} \right) \tag{4.24}$$

Remaining Head at Outlet – P_t (m head)

$$Pt = P - hf \qquad (4.25)$$

The model produces outputs of total length of pipe required, friction loss through the grid, number of pipes required and the length of each pipe. The length of each pipe is a user defined input and is reported here as a reminder to the user. The number of pipes required is simply the total length divided by the length of each pipe.

Each 6 metre cooling grid manifold has 30 pipe outlets, and the cooling pipes are also produced in 6 metre lengths. Knowing this, the user can then use the model to vary the length of each pipe, in multiples of 6 metres, to gain an output from the model of the number of pipes required to as close to a multiple of 30 as possible. The user can then design the appropriate sized cooling grid using these values.

For example, with the individual pipe length defined by the user as 18.0 metres, the model declares that 77 pipes of this length is required to transfer the calculated amount of heat in a hypothetical cooling grid system. Therefore, the cooling grid would need to be 18.0 metres long by 3 manifolds, or 18.0 metres, wide. This would include 13 extra pipes and would therefore be over designed.

By varying the length of each pipe to 24.0 metres, the model then declares that only 55 pipes are required for cooling and the system would now be 24.0 metres long by 2 manifolds, or 12 metres, wide. Only 5 extra pipes would be required, which is an increase in design efficiency.

4.2 Sensitivity Analysis

A sensitivity analysis of the spreadsheet design model was conducted at the beginning of the project to identify important variables. By identifying the most influential components of the design, the testing and experimentation phases were better able to focus on analysing these areas. Each input and some constants were varied by a percentage and the relative change in the model's output was noted. The percentage by which each input was varied depended upon their initial values and their purpose in the design. For example, the temperature of the pond could not be varied by 50% as it may become higher than the bore inlet temperature which is highly unlikely in a real world situation. Table 4.1 below outlines the results of the sensitivity analysis.

Table 4.1 Sensitivity Analysis Results

Variable	**Material**		**Model Output (No. of pipes)**	**Variance**
Thermal Conductivity *k* (W/m.K)	Copper k = 380		52	0 %
	Aluminium k = 240		52	0 %
	Stainless Steel k = 17		54	3.8 %
Variable	**% Varied**	**Initial Value**	**Output (No. of pipes)**	**Variance**
Maximum Flowrate *Q* (L/s)	+ 50 %	52	78	+ 50 %
	- 50 %		26	- 50 %
Bore Temperature T_i (°C)	+ 10 %	52	68	+ 33 %
	- 10 %		33	- 33 %
Pressure head at Inlet P (m)	+ 50 %	52	52	0 %
	- 50 %		52	0 %
Outlet Temperature Required T_o (°C)	+ 10 %	52	27	- 48 %
	- 10 %		90	+ 73 %
Pond Temperature T_p (°C)	+ 10 %	52	71	+ 37 %
	- 10 %		41	- 21 %

From the sensitivity analysis, the most important variables were identified as maximum flowrate as well as the outlet, bore and pond temperatures. The required outlet temperature proved to be the most influential factor with larger variances in the model output than the other input variables. For design purposes it is important to note that this required outlet temperature remains constant. Maximum flowrate, Q, affected the model output by the same value as it was varied. The bore, T_i, and pond, T_p, temperatures altered the model output by slightly greater than that by which the variables were altered. Pressure head at inlet had no effect on the model output which was expected as this value is used in pressure and friction calculations only.

Interestingly, the thermal conductivity, k, of the pipe material had no significant impact on the model output. This was quite surprising as indicated by the change from copper to stainless steel values of more than 2200% yielding a variation in model output of only 3.8%.

The results of the sensitivity analysis provided an overall perspective of the model's ability to cope with change and allowed for the selection of alternative pipe materials to be unrestricted by their relative thermal conductivity values. The sensitivity of the other various inputs will allow for a more guided model analysis and optimisation.

The following chapter outlines the field testing procedure, justification and limitations of the procedure as well as the heat transfer prediction methods.

CHAPTER 5

EXPERIMENTAL METHODOLOGY

5.0 Experimental Methodology

5.1 Field Testing Procedure

Testing of alternative cooling grid pipe materials was conducted on the ‘Beverleigh’ property bore, 5 kilometres east of Dirranbandi, Qld. The bore itself has a maximum temperature of 62℃ and maximum discharge of approximately 15 L/s. The headworks of the bore have been recently rehabilitated by NR&W staff and the property was in the process of becoming fully serviced by pipelines to tanks and troughs. A 16m by 16m cooling pond and 12m by 12m grid was installed approximately 30 metres north east of the bore head. The cooling grid had not yet been in service because of a damaged coupling to a manifold.

The three pipe materials to be tested were aluminium (28.4mm outer diameter (OD)), copper (19.1mm OD), and stainless steel (25.4mm OD). The testing apparatus was set up on the western edge of the cooling grid within the dry pond with steel posts and hooks to hold the single 12m pipe material approximately 0.5m above the pond floor (see Figure 5.1). The water inlet and outlet temperatures were recorded using an EMS 050D data logger equipped with RTD PT100 temperature probes. The probes were inserted into the centre of the flow using a blanking plug in an upright poly T-junction and were sealed using rubber grommets. The data logger recorded readings at 15 second intervals.

Discharges representing 1, 3, 5 and 7 L/s through an entire grid were simulated in the single pipe using 0.017, 0.05, 0.083 and 0.117 L/s flowrates respectively. This was calculated by dividing the flow by the number of pipes within the grid, in this case 60. These flows were chosen because of their general representation of the overall operating spectrum of cooling grid systems as well their particular flow characteristics. The velocity profile and Reynolds number of the 1 and 3 L/s flowrates indicates laminar and transitional flow respectively, whereas the 5 and 7 L/s flowrates represented the turbulent end of the spectrum. Kinematic viscosity, v, was varied to 5.0 x 10^{-6} m^2/s for water at 60 °C.

Figure 5.1 Air Test Apparatus

The first series of tests were conducted with the pipe suspended in air. The air transfer medium was chosen to provide a comparison to the traditional submerged pipe configuration and also to investigate this water cooling application. Each flowrate test was conducted for 20 minutes in air for each pipe material to reach equilibrium, resulting in an 80 minute test for each material (see Figure 5.2).

Ambient temperatures at the upstream (U/S) and downstream (D/S) ends of the pipe material approximately 2.5cm from the pipe, (horizontally), were recorded at 4 minute intervals using a handheld digital thermometer. Waste water was allowed to flow into the centre of the pond.

These tests were conducted over a two day period. The location, time, date, wet and dry bulb temperatures, relative humidity, wind speed and direction as well as general weather conditions were observed at the beginning and during each test.

Figure 5.2 Data logger and manual readings during pipe in air test

At the conclusion of the pipe (in-air) tests the pond was filled from the grid's inlet pipe to a depth of approximately 1 metre (see Figure 5.3). The pond was then allowed to cool overnight.

All tests were repeated for each pipe material while submerged in water over a one day period with one significant change in experimental design. Following each individual flow test, the system was flushed with a high flowrate to increase the water temperature at the pipe inlet for the beginning of the next test. This was conducted to ensure an appropriate temperature gradient between the water in the pipe and the water in the pond.

Again the location, time, date, wet and dry bulb temperatures, relative humidity, wind speed and direction as well as general weather conditions were observed at the beginning and during each test. See Chapter 6 for results.

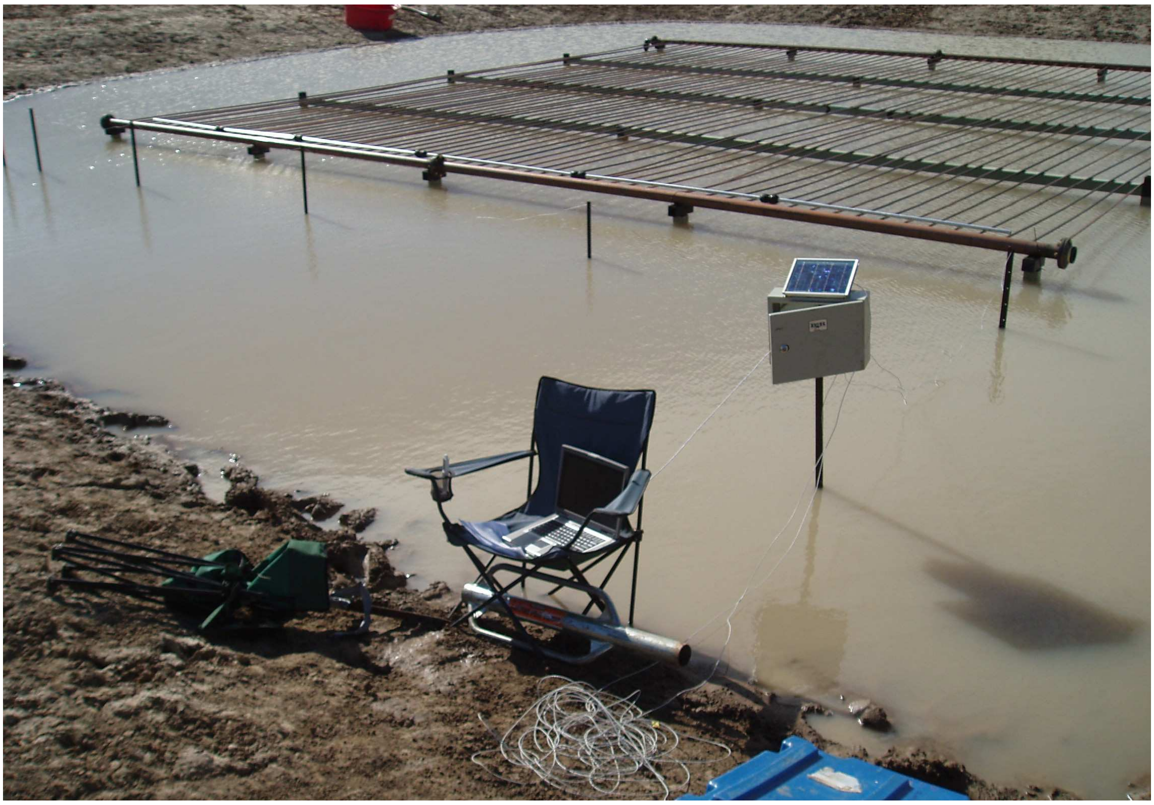

Figure 5.3 Water test apparatus with submerged test material fixed to steel posts

To maintain accuracy in experimental design the RTD PT100 temperature probes and the digital thermometer were calibrated prior to testing. Each probe and thermometer was submerged in ice water for 10 minutes. A control temperature was recorded using a glass mercury thermometer which was used as the benchmark temperature. The probes required adjustment using the logger software package and were retested in the ice water. The digital thermometer required no alterations.

Following this first calibration the probes and the digital thermometer were allowed to reach room temperature for a period of 1 hour. Comparisons were then conducted against the mercury thermometer, no alterations were necessary.

Each flowrate during testing was regulated using a 3L graduated cylinder and a stopwatch. A tap was connected at the pipe outlet to adjust the flows. To achieve the desired flowrates of 0.017, 0.05, 0.083 and 0.117 L/s the time taken to fill 2 litres of the cylinder was measured and compared to the calculated required times of 118 seconds, 40 seconds, 24 seconds and 17 seconds respectively. The flows could then be adjusted allowing a variation of 0.2 seconds to account for measurement and reaction time discrepancies.

5.2 Limitations on Experimentation

During the experimental design and testing phases of the project, certain limitations were encountered. Due to material availability problems and production constraints, the pipe diameter of each material differed slightly. The copper was 19.1mm outer diameter (OD), the stainless steel was 25.4mm OD and the aluminium was 28.4mm OD. This created different surface areas for heat transfer and variations in flow parameters between each material.

Originally, 10 pipes of each material were to be tested by attaching them to a cooling grid in situ. It was thought at the time that this method would give a more accurate representation of the heat transfer for each material. This was proven to be unfeasible because of the high costs and funding constraints.

Also, the experimental design required alteration during testing to account for the heat loss in the connections between the bore head and the grid inlet. The low flowrates allowed for a significant time period for the water to cool in the PEX pipe connections. This required an additional 'flushing' of the system after each test to maintain a large temperature gradient between the water in the pipe and the pond.

5.3 Experimental Design Justification

The varied pipe diameters and surface areas between the different materials indicated that the heat transfer between the material and the air or water would be affected. It was then important to note the relative comparisons between the different surface areas and also how the flow characteristics would change accordingly. The flow parameters, such as Reynolds number, were then calculated individually before testing to verify the flow characteristics required. The difference in surface area for heat transfer is accounted for in the design model so it was only necessary to note the relative differences for comparison when analysing the results.

The use of a single test pipe, because of monetary constraints, was justified when the standard operating conditions of a cooling grid was analysed. Normally, a water molecule to be cooled would only travel through a single pipe in an entire grid, assuming equal distribution of water discharge in each pipe. Therefore, to simulate this process only a single test pipe is required for the desired cooling effect to take place. By varying the flowrate from that of an entire grid to represent a single pipe, the normal operating conditions of a cooling grid can be simulated.

Heat loss through the connections to the bore head was minimised by ‘flushing’ of the system after each test to maintain heat transfer. This practice had a positive impact on the experimentation as each flowrate test began at the same temperature which allowed for easier comparisons during the results analysis stage.

5.4 Heat Transfer Predictions

It was impossible to accurately model the pipe in-air transfer tests because of the nature of the spreadsheet model. This was because of the certain constants and parameters such as water fouling factors, values from graphs and calculated heat transfer coefficients, were specifically designed for the water transfer situation. However, the measured air transfer results provided sufficient data to allow predictions and conclusions to be drawn on its applications to this form of water cooling.

To accurately model the water transfer tests using the design spreadsheet some modification was necessary. Firstly, the average measured pipe inlet and outlet temperatures were calculated from the experimental data during the period of heat transfer equilibrium for each flowrate for every material.

Secondly, it was important to identify the variables in the spreadsheet that could be modified without affecting the underlying theory of the model and thirdly, to identify the variables which had been physically measured during testing. It was discovered that by using the average measured pond and inlet temperatures at equilibrium and the pipe length as benchmarks, it was possible to vary the outlet temperature to predict the modelled amount of heat transfer in each situation.

For example, to gain an output of 12.0m length of pipe required, with measured temperatures of 33 ℃ for the pond, and 54 ℃ for the inlet, the outlet temperature could be varied, to say 46 ℃. Therefore, this method could be used to discover the modelled amount of heat transfer which can then be used as a comparison to the actual measured heat transfer.

CHAPTER 6
EXPERIMENTAL RESULTS & MODEL VALIDATION

6.0 Experimental Results & Model Validation

6.1 Heat Transfer Test Results

The results of the heat transfer experiments conducted at the 'Beverleigh' property bore for aluminium, copper and stainless steel pipe materials are outlined below. The EMS 050D data logger recorded the inlet and outlet temperatures from the experimental apparatus indicated below by the blue and red lines respectively. It is important to identify that the higher flowrates were measured at the beginning of each test. Figures 6.1, 6.2 and 6.3 represent the pipe in-air tests.

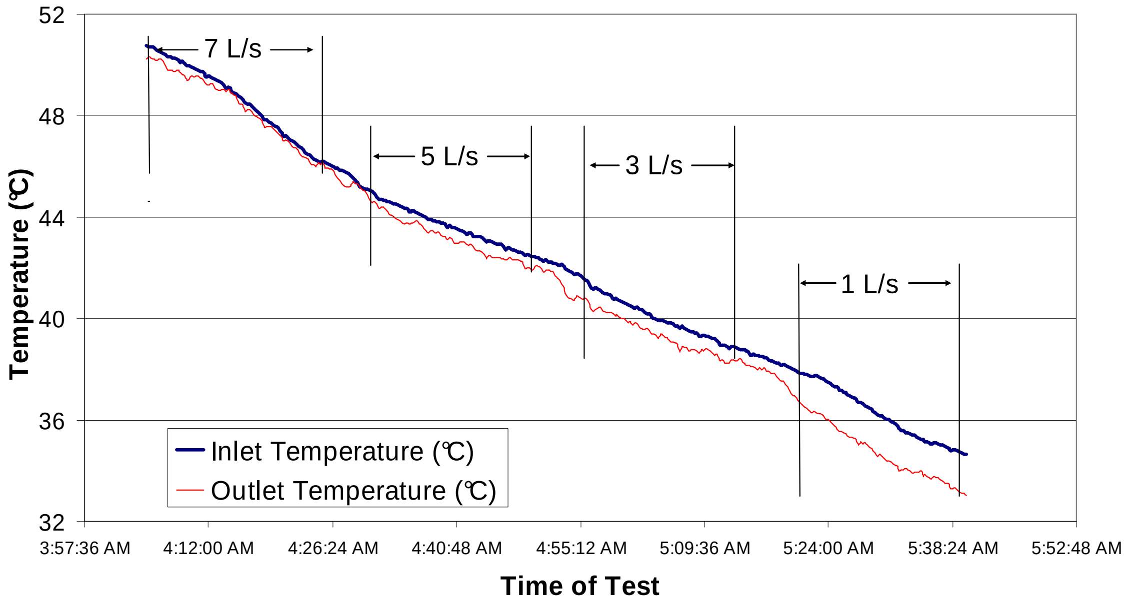

Figure 6.1 Pipe in-air test results indicating inlet and outlet temperatures as well as the 20 minute regions of varied flowrates for the ALUMINIUM pipe material.

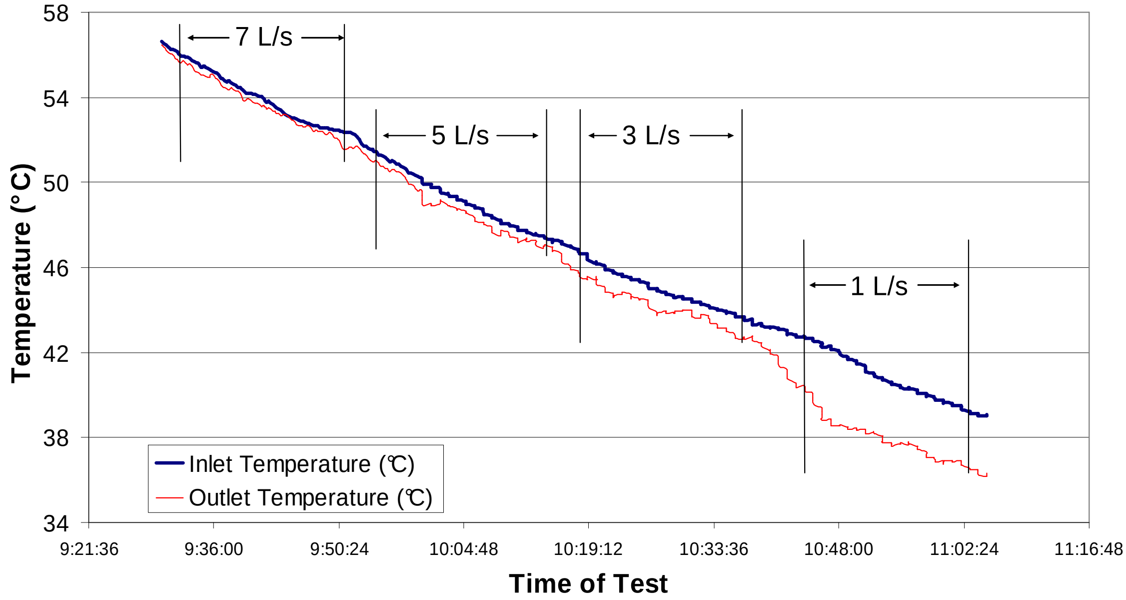

Figure 6.2 Pipe in-air test results indicating inlet and outlet temperatures as well as the 20 minute regions of varied flowrates for the COPPER pipe material.

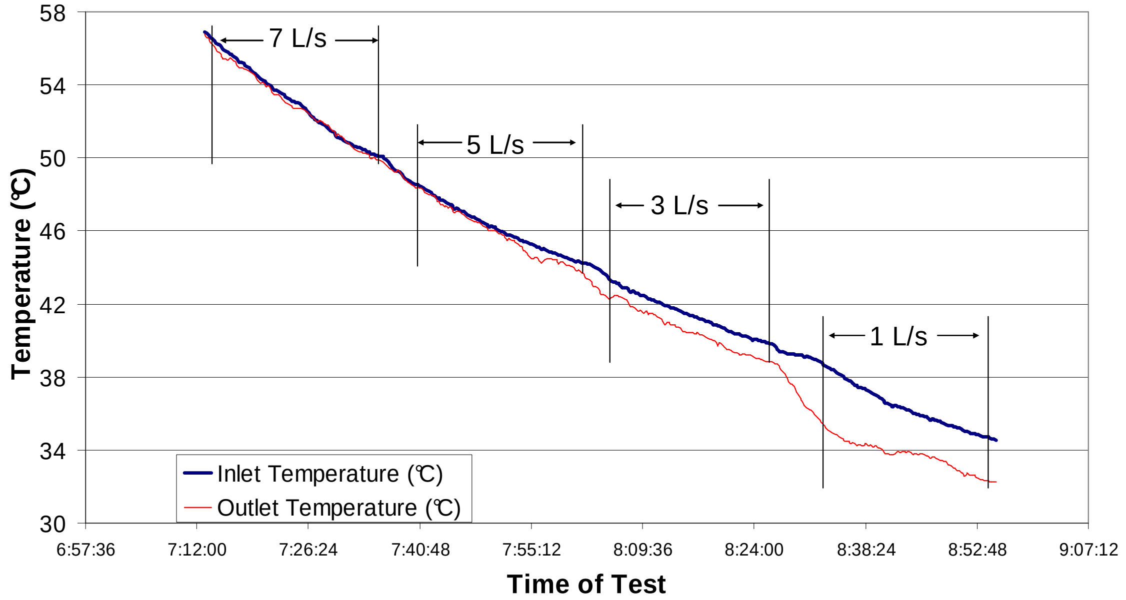

Figure 6.3 Pipe in-air test results indicating inlet and outlet temperatures as well as the 20 minute regions of varied flowrates for the STAINLESS STEEL pipe material.

Similarly, the heat transfer in water experimental data outlined below in the graphs of inlet (blue) and outlet (red) temperatures for aluminium (Figure 6.4), copper (Figure 6.5) and stainless steel (Figure 6.6) pipe materials. The higher flowrates were measured at the beginning of each water test as well.

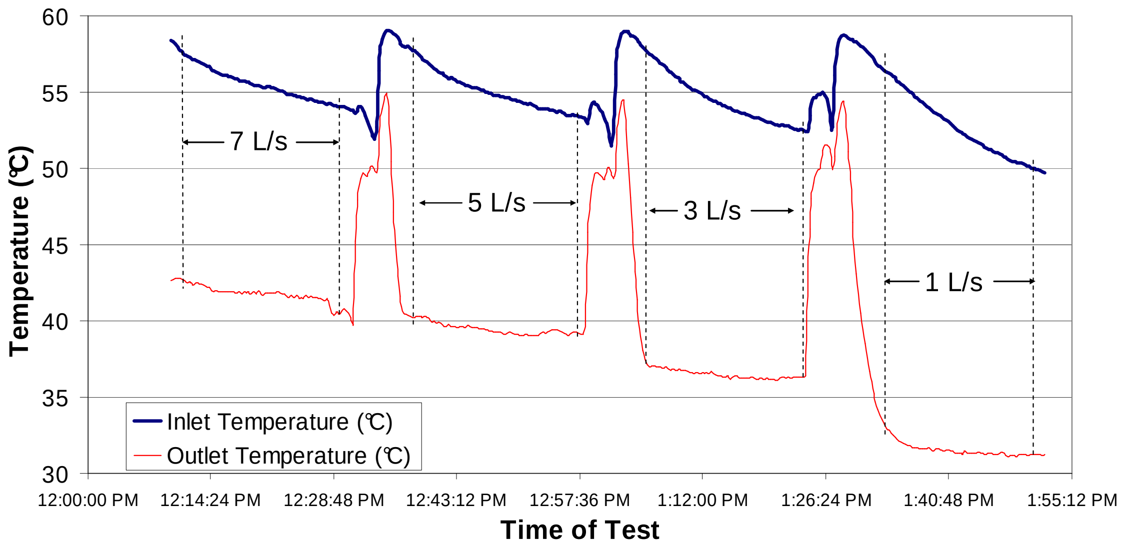

Figure 6.4 Pipe in-water test results indicating inlet and outlet temperatures as well as the 20 minute regions of varied flowrates for the ALUMINIUM pipe material.

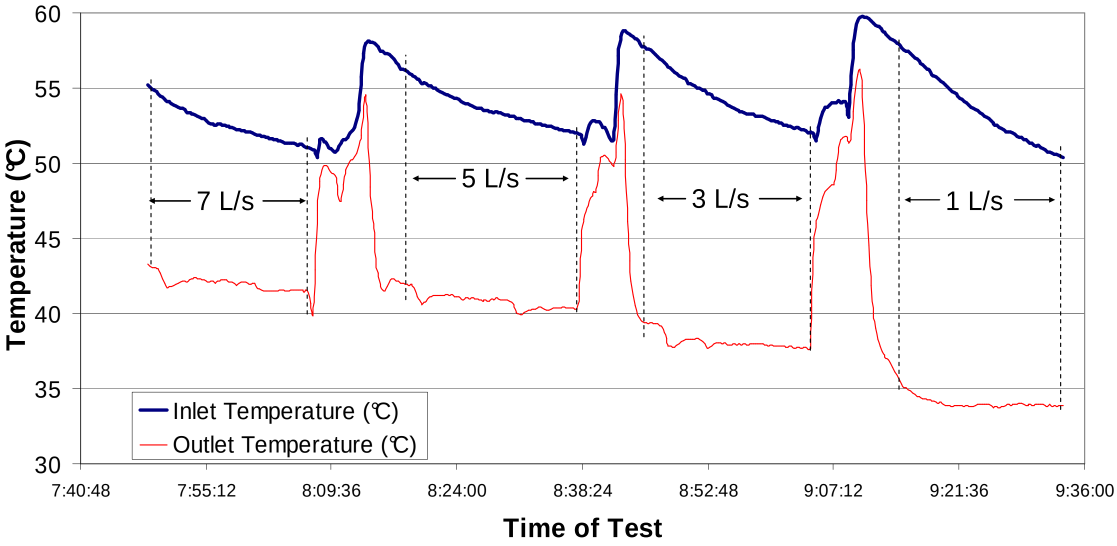

Figure 6.5 Pipe in-water test results indicating inlet and outlet temperatures as well as the 20 minute regions of varied flowrates for the COPPER pipe material.

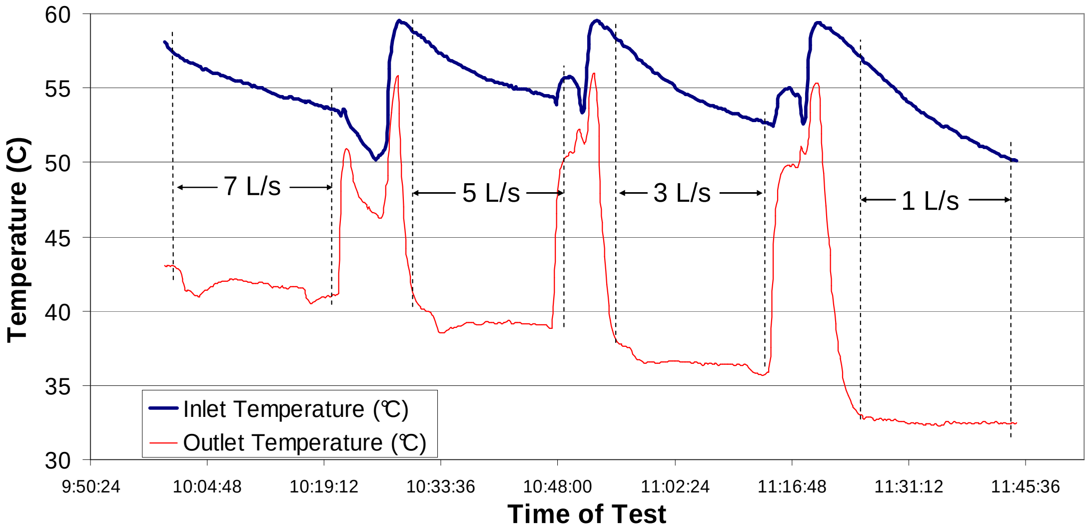

Figure 6.6 Pipe in-water test results indicating inlet and outlet temperatures as well as the 20 minute regions of varied flowrates for the STAINLESS STEEL pipe material.

6.2 Experiment Conditions and Ambient Temperatures

Manual readings of ambient U/S and D/S air (pipe in-air) and pond (pipe in-water) temperatures as well as weather conditions during each heat transfer test are outlined below in Tables 6.1a, 6.1b and 6.1c for the pipe in-air tests and Tables 6.2a, 6.2b and 6.2c for the pipe in-water tests. These results were integral when modelling the equilibrium water transfer tests and allowed the actual pond temperatures to be used in modelling the system output.

Test: Aluminium Air Test

Location: 'Beverleigh' Date: 30/07/2008 Start Time: 4.05 p.m.

Wet Bulb Temp: 9.5 ℃ Dry Bulb Temp: 18 ℃

Relative Humidity: 0 % Wind Speed: 2 m/s Wind Direction: SW

Weather Conditions: fine Pipe Height: 0.5 m

Table 6.1a Aluminium Air Test Ambient Temperatures (℃)

Time (mins)	1 L/s		3 L/s		5 L/s		7 L/s	
	U/S	D/S	U/S	D/S	U/S	D/S	U/S	D/S
0	14.2	14.2	17.7	17.7	17.7	17.7	18.0	18.0
4	14.0	14.0	17.0	17.0	17.5	17.5	18.0	18.0
8	13.5	13.5	16.4	16.3	17.0	17.0	18.0	18.0
12	13.2	13.2	16.0	16.0	17.0	17.0	18.5	18.5
16	12.7	12.7	15.5	15.5	17.0	17.0	18.5	18.5
20	12.1	12.1	14.8	14.8	17.0	17.0	18.0	18.0

Test: Copper Air Test

Location: 'Beverleigh' Date: 31/07/2008 Start Time: 9.30 a.m.

Wet Bulb Temp: 11.0 ℃ Dry Bulb Temp: 16 ℃

Relative Humidity: 0 % Wind Speed: 0 m/s Wind Direction: NA

Weather Conditions: fine Pipe Height: 0.5 m

Table 6.1b Copper Air Test Ambient Temperatures (℃)

Time (mins)	1 L/s		3 L/s		5 L/s		7 L/s	
	U/S	D/S	U/S	D/S	U/S	D/S	U/S	D/S
0	21.0	20.7	20.0	20.0	19.0	19.0	17.8	17.7
4	21.3	21.0	20.0	20.0	19.0	19.0	17.9	17.9
8	21.7	21.1	20.1	20.0	19.2	19.1	18.0	18.0
12	22.0	21.3	20.2	20.2	19.4	19.3	18.0	18.0
16	22.3	21.4	20.4	20.3	19.6	19.6	18.5	18.5
20	22.5	21.6	20.5	20.4	19.9	19.8	19.0	18.9

Test: Stainless Steel Air Test

Location: 'Beverleigh' Date: 31/07/2008 Start Time: 7.12 a.m.

Wet Bulb Temp: 1.5 ℃ Dry Bulb Temp: 2.5 ℃

Relative Humidity: 0 % Wind Speed: 0 m/s Wind Direction: NA

Weather Conditions: fine Pipe Height: 0.5 m

Table 6.1c Stainless Steel Air Test Ambient Temperatures (℃)

Time (mins)	1 L/s		3 L/s		5 L/s		7 L/s	
	U/S	D/S	U/S	D/S	U/S	D/S	U/S	D/S
0	12.8	12.7	11.8	11.7	8.4	8.4	4.4	4.3
4	13.4	13.4	12.3	12.2	8.9	8.6	4.5	4.4
8	14.0	14.0	12.8	12.7	9.6	9.5	6.3	6.1
12	14.4	14.4	12.6	12.5	10.4	10.3	6.3	6.1
16	14.4	14.4	12.5	12.4	9.5	9.4	6.5	6.4
20	15.0	15.0	12.7	12.6	11.3	11.0	7.5	7.2

It is important to note that the higher flowrate tests were conducted first for each pipe in-water test resulting in higher ambient pond temperatures for these higher flows.

Test: Aluminium Water Test

Location: 'Beverleigh' Date: 01/08/2008 Start Time:12.10 p.m.

Wet Bulb Temp: 19.5 °C Dry Bulb Temp: 22.4 °C

Relative Humidity: 0 % Wind Speed: 2 m/s Wind Direction: N

Weather Conditions: fine Pipe Height: 0.5 m Water Height: 1.0 m

Table 6.2a Aluminium Water Test Ambient Pond Temperatures (°C)

Time (mins)	**1 L/s**		**3 L/s**		**5 L/s**		**7 L/s**	
	U/S	**D/S**	**U/S**	**D/S**	**U/S**	**D/S**	**U/S**	**D/S**
0	30.1	30.1	30.4	30.4	30.7	30.7	31.0	31.0
4	30.1	30.1	30.4	30.4	30.7	30.7	30.9	30.9
8	30.0	30.0	30.3	30.3	30.6	30.6	30.8	30.8
12	30.0	30.0	30.3	30.3	30.6	30.6	30.8	30.8
16	29.9	29.9	30.2	30.2	30.5	30.5	30.7	30.7
20	29.9	29.9	30.2	30.2	30.5	30.5	30.7	30.7

Test: Copper Water Test

Location: 'Beverleigh' Date: 01/08/2008 Start Time: 7.48 a.m.

Wet Bulb Temp: 10.0 ℃ Dry Bulb Temp: 13.0 ℃

Relative Humidity: 0 % Wind Speed: 2 m/s Wind Direction: N

Weather Conditions: fine Pipe Height: 0.5 m Water Height: 1.0 m

Table 6.2b Copper Water Test Ambient Pond Temperatures (℃)

Time (mins)	**1 L/s**		**3 L/s**		**5 L/s**		**7 L/s**	
	U/S	**D/S**	**U/S**	**D/S**	**U/S**	**D/S**	**U/S**	**D/S**
0	32.3	32.3	32.7	32.7	32.8	32.8	33.0	33.0
4	32.3	32.3	32.7	32.7	32.8	32.8	33.0	33.0
8	32.3	32.3	32.6	32.6	32.8	32.8	32.9	32.9
12	32.2	32.2	32.6	32.6	32.8	32.8	32.9	32.9
16	32.2	32.2	32.5	32.5	32.8	32.8	32.9	32.9
20	32.2	32.2	32.5	32.5	32.8	32.8	32.9	32.9

Test: Stainless Steel Water Test

Location: 'Beverleigh' Date: 01/08/2008 Start Time:10.00 a.m.

Wet Bulb Temp: 16.0 ℃ Dry Bulb Temp: 18.7 ℃

Relative Humidity: 0 % Wind Speed: 2 m/s Wind Direction: N

Weather Conditions: fine Pipe Height: 0.5 m Water Height: 1.0 m

Table 6.2c Stainless Steel Water Test Ambient Pond Temperatures (℃)

Time (mins)	**1 L/s**		**3 L/s**		**5 L/s**		**7 L/s**	
	U/S	**D/S**	**U/S**	**D/S**	**U/S**	**D/S**	**U/S**	**D/S**
0	31.3	31.3	31.5	31.5	31.7	31.7	32.0	32.0
4	31.3	31.3	31.5	31.5	31.7	31.7	32.0	32.0
8	31.3	31.3	31.5	31.5	31.7	31.7	31.9	31.9
12	31.2	31.2	31.4	31.4	31.6	31.6	31.8	31.8
16	31.2	31.2	31.4	31.4	31.6	31.6	31.7	31.7
20	31.1	31.1	31.4	31.4	31.6	31.6	31.7	31.7

6.3 Average Equilibrium and Modelled Temperatures

A region of heat transfer equilibrium, (or approaching equilibrium), for the water tests was observed over the concluding stages of each flowrate test for each pipe material model as outlined in Section 5.4. The inlet and outlet temperatures were taken from this time period and averaged as shown in Table 6.3. The temperature difference between inlet and outlet (ΔT) was also calculated, Table 6.4. For comparison, modelled values of ΔT were calculated using the design model, see Table 6.5.

Table 6.3 Average Equilibrium Temperatures and Differences (℃)

Flow Q (L/s)	Aluminium Average Temps			Copper Average Temps			Stainless Steel Average Temps		
	Inlet	Outlet	ΔT	Inlet	Outlet	ΔT	Inlet	Outlet	ΔT
7	54.541	41.546	12.995	51.457	41.517	9.94	54.474	41.645	12.829
5	53.92	39.195	14.725	52.456	40.324	12.132	54.936	39.16	15.776
3	52.796	36.254	16.542	52.599	37.815	14.784	53.518	36.421	17.097
1	50.253	31.227	19.026	51.036	33.903	17.133	50.652	32.466	18.186

Table 6.4 Measured ΔT (℃)

Flowrate Q (L/s)	Aluminium	Copper	Stainless Steel
7	12.995	9.940	12.829
5	14.725	12.132	15.776
3	16.542	14.784	17.097
1	19.026	17.133	18.186

Table 6.5 Modelled ΔT (℃)

Flowrate Q (L/s)	Aluminium	Copper	Stainless Steel
7	11.241	7.407	10.264
5	13.120	9.756	12.736
3	15.646	12.799	14.818
1	18.173	16.766	17.422

To gain a better understanding of the spreadsheet model's performance the difference between the measured and modelled ΔT's for each flowrate were calculated and converted to a percentage of the measured ΔT values. The results are shown in Figure 6.7.

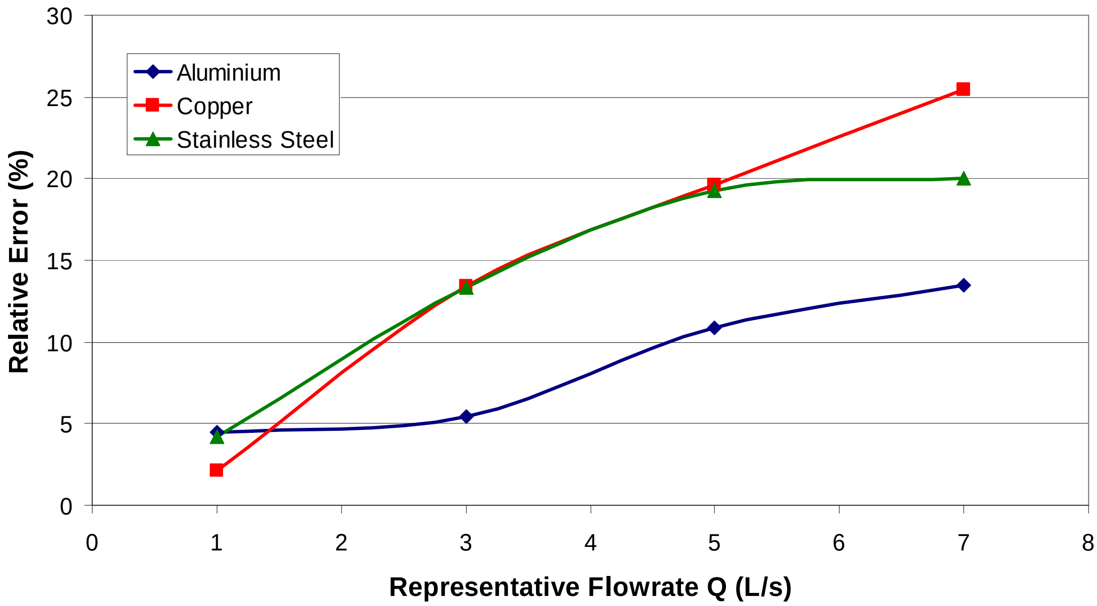

Figure 6.7 The relative error of measured ΔT vs modelled ΔT at each flowrate for all three pipe materials.

From Figure 6.7 it was evident that as the flowrate increased, the relative error of the modelled ΔT versus measured ΔT values also increased. This indicated that under the current copper cooling grid model, all systems were being over designed by as much as approximately 25% at the higher design flowrates. However, to gain an understanding of the actual implications of this variance between modelled and measured ΔT's, it was necessary to return to the sensitivity analysis of the model.

To determine the impact of the relative error on the overall performance of the model, the temperature difference between the bore temperature, T_i, and the required outlet temperature, T_o, was varied by ±25% in the sensitivity analysis of the spreadsheet model inputs. The results are shown in Table 6.6. Other inputs remained constant for copper pipe at 7 L/s.

Table 6.6 Model Validation

Bore Temp T_i (℃)	**Outlet Temp T_o (℃)**	**ΔT (℃)**	**Varied (%)**	**Model Output (no. of pipes)**	**Variance (%)**
60	45	15	0	61	0
56.25	45	11.25	- 25	50	18.3
63.75	45	18.75	+ 25	70	14.8

To put this in real terms, the actual impact of the -25% relative error between measured and modelled ΔT's, (to replicate an over designed system), resulted in a variation of approximately 18.0% in the model output.

This value, however, should be analysed in terms of the number of pipes required and not the actual percentage difference to appreciate its impact. The number of pipes required was reduced to 50 from 61, which in a design situation would still be considered as a 2 manifold grid or 12 metre wide grid which utilises 60 pipes. This means that the overall implications of the 25% relative error is actually very minimal when analysed with respect to the entire system and cooling grid design procedure.

From these results it was concluded that although the model was over designed, the actual implications were insignificant with respect to the entire system. The slight variation will actually provide a small factor of safety for the model which can be considered as valid.

The following chapter will further discuss the in-air and in-water test results along with an optimisation of the cooling grid design. Implications of this work will also be analysed.

CHAPTER 7

DISCUSSION & IMPLICATIONS

7.0 Discussion & Implications

7.1 Heat Transfer in Air Tests

The heat transfer results from the pipe in-air tests were as expected with the conduction coefficient 21 times less for air than water (Janna, 2000). Over all the three pipe materials tested, the results indicated that there was no significant heat transfer or cooling effect when the heat transfer medium was air.

During the higher flowrate tests, the general temperature difference between pipe inlet and outlet was less than 1 ℃. A slight incre ase in this amount occurred during the lower flowrates. This increase was unexpected because of the reduced amount of fluid mixing that was experienced while undergoing laminar flow. The reason for the higher heat transfer capabilities was determined to be the increased amount of time available for heat transfer in the test pipe at the lower flowrates.

To gain the same performance from a pipe in-air cooling system as a pipe in-water cooling system, the length of pipe required would theoretically be 21 times that of the pipe in-water system. This is because of the significantly reduced conduction coefficient and lack of the evaporative cooling effect. Therefore, on that basis a simple cooling grid in-air would not be a viable option for the cooling of artesian bore water as the increased costs of materials would far outweigh the costs of cooling pond construction.

Other possible complications would be solar radiation heating the pipes during the hotter periods of the year which also happens to be the same period of higher system outputs to stock. This would require some form of shade structure. Also, the large area of property required for the construction of an in-air system would become a financial disadvantage for the landholder because of increased maintenance and loss of productive area.

7.2 Heat Transfer in Water Tests

Overall, the heat transfer in water test results indicated the validity of the design model as outlined in Section 6.3. Other significant outcomes include the individual pipe performance and the flow characteristic performance.

Comparatively, no individual pipe material performed at a higher level than any other. Taking into consideration the slightly different pipe diameters, there is little discernable difference in heat transfer with all of the temperature gradients remaining relatively the same over each material test. A trend exists in the results where as the flowrate is decreased, a larger temperature gradient is created between the pipe inlet and outlet temperatures with the pipe inlet value remaining relatively constant for each flowrate. This trend is evident for all three pipe materials and indicates that the results obtained in the preliminary sensitivity analysis, i.e. that the thermal conductivity value, k, of the pipe material has little effect on the model output, are valid.

Because of the little effect that the thermal conductivity value had on overall heat transfer, it was necessary to analyse the model to discover which of the heat transfer mechanisms were doing all the ‘work’, so to speak. After looking at the overall heat transfer coefficient, U, and its equation 4.20 in Section 4.1, it became evident that the convective heat transfer coefficients for natural and forced convection within the pond and pipes respectively were the main contributing factors to the removal and dissipation of the heat from the artesian bore water.

The conclusion that the physical convective forces were more important than the physical characteristics of the actual pipe material in question, or even the evaporative cooling effect on the pond surface, will allow for a more flexible design optimisation where other contributing factors, such as costs, can be more involved in the decision making process.

In respect to the flow characteristics within the pipe, turbulent conditions were not required at all times to maintain significant mixing for heat transfer. This is evident in Figures 6.4 to 6.6. The lower flowrates of 3 L/s and 1 L/s, which represented the transitional and laminar flow regions respectively, were observed to maintain higher temperature gradients between pipe inlet and outlet temperatures than that of the higher flowrates. In the 1 L/s flowrate tests, a notable jump in heat transfer was observed as with the pipe in-air tests. This was due to the increased amount of available time for heat transfer as the water passed through the pipe being tested.

During experimentation the height of water above the apparatus was set at 0.5m. This was due to height restrictions for the testing procedure because the pipe material being tested required changing and a larger depth would have produced problems in terms of tightening joins and safety.

Under normal operating conditions the cooling grid is submerged under 2.0m of water, however the 0.5m depth used for testing did not affect the convection capabilities of the pond or contribute to any inconsistencies in design. This was because the ambient temperatures of the pond were recorded to be included in the model comparisons and the apparent lack of significant convective currents within the pond during testing.

In summary, the pipe in-water heat transfer experiments provided temperature data for the spreadsheet model analysis and validation, proved that turbulent flow conditions are not required in the design to maintain heat transfer and also that the depth of the submerged pipe does not need to be a minimum of 2.0m for natural convection current to dissipate heat efficiently.

7.3 Design Optimisation

To optimise the current cooling grid design it was necessary to take into account costs, material performance and availability, pipeline flow characteristics and maintenance requirements for the materials in question. Using the commercial material costs outlined in Table 3.5 it was concluded that the aluminium pipe material is a cheaper option than copper or stainless steel. Being commercial costs these prices would come down for bulk government orders of this magnitude for DNR&W.

The performance of the three pipe materials selected for this investigation can be measured in terms of modelled versus measured relative errors, resistance to corrosion and material availability. The modelled versus measured relative errors depicted in Figure 6.7 indicate a general trend of increasing error with increasing flowrate beginning as low as 2% at 1 L/s up to 25% at 7 L/s. Copper pipe was observed to perform the worst having a greater variation in relative error over the flowrates analysed than the other two materials. Aluminium performed the best having a steady variation in relative error from 4.5% at 1 L/s to 13.5% at 7 L/s. The stainless steel results fell in between the other two materials.

Corrosion resistance is another important characteristic of pipe materials for cooling grids. All three materials in question form a self-healing protective oxide coating when exposed to oxygen, as outlined in Chapter 3, which was a critical factor in the material selection.

The availability of pipe materials is dependent upon supply and demand factors. Of the three materials copper is the most readily available due to its application in commercial and industrial plumbing. Aluminium and stainless steel pipe are also readily available from most metal companies in a range of diameters and can be ordered in bulk.

From these results aluminium was determined to be the better performer because of the smaller relative errors between measured and modelled temperature differences than the other two materials. The corrosion resistance and availability of materials analysis indicated no significant contrast between the three pipe materials.

The conditions of flow within the pipelines during the experimentation phase of the project were designed to be similar for each material, investigating the laminar, transition and turbulent regions of flow. The results obtained from each pipe in-water test indicated different heat transfer capabilities within each region of flow. This was correlated in all three materials tested. The similarities in results from all three materials led to the conclusion that the flow characteristics in the pipelines were not a contributing factor in determining an optimised design.

Maintenance of cooling grids is required for the removal of algal growth from the pipes after an extended period of operation. This maintenance is conducted to improve the exterior of the pipes and restore the system's heat transfer capabilities. The algal growth is promoted because of the warmth of the cooling grid which provides an environment for algae to develop. With all pipe materials being able to conduct this warmth, it is impossible to identify which material will perform better or require less maintenance than the others.

After analysing the costs, material performance and availability, pipeline flow characteristics and maintenance requirements of the materials investigated, it was evident that the most suitable pipe material to be used in the current cooling grid design was aluminium. Aluminium exhibited a lower cost, smaller relative error in modelled versus measured ΔT than copper and stainless steel. Aluminium is also resistant to corrosion, readily available and requires minimal maintenance.

7.4 Implications

By validating the spreadsheet model used in the design of cooling grids, DNR&W can now be assured of its accuracy for future schemes. The data collected has allowed for comparisons to be drawn between water and air as heat transfer mediums, resulting in air being discounted without some form of shading or evaporative cooling effect to aid in heat dissipation. Water as a heat transfer medium proved to be the better mechanism to cool hot artesian bore water under the current design.

The comparisons of pipe materials indicated that aluminium would be a better alternative than the current copper cooling grid pipes. Aluminium surpassed copper and stainless steel as outlined above and will be strongly recommended as the alternative cooling grid pipe material. This result was the most important outcome from the project. To ensure the efficient use of resources and reduce the overall capital investment in cooling of artesian groundwater it is important that this recommendation be considered by DNR&W for immediate implementation.

However, it is important to take into account the overall picture to truly appreciate the implications of research into the cooling of artesian groundwater. For example, the operating cooling requirements of a cooling grid, for which it will be experiencing for 99% of its design life, is substantially less than that of the initial system filling cooling requirements that the cooling grids are designed for. This is carried out to guarantee that the entire system can be filled in a 24 hour period. Considering the tanks at the designated watering points are designed to hold a minimum of two days stock water drinking supply, why do we need the 24 hour system fill?

It would be more efficient to conduct a monitored fill of the system over a period of 48 or 72 hours with a lower flowrate which would require a smaller sized cooling grid. This smaller cooling grid would reduce costs for the entire system and would be more fully utilised during operation than one designed for a 24 hour fill. Adding to this point is the cooling of the bore head after piping which has been observed on previous schemes. This is due to the lower discharge at the bore and increased pressure that results after a bore is capped and piped. The bore water temperature at the surface is reduced, further reducing the requirement of cooling.

Assuming this bore head cooling effect is occurring on all systems, can we introduce a temporary or transportable cooling grid system to manage heat transfer during the system fill? To compensate for the reduced cooling capacity a larger distance of the heat tolerant PEX pipe could be included between the bore and distribution heads to ensure against failure during a higher output in the summer months. Therefore, the question becomes are cooling grids required at all?

Another important point to note is that tradition can sometimes cloud our judgement. Just because cooling grids have been used in the past to cool artesian bore water, there is no reason why we cannot change the design completely. An entirely different cooling technique, such as the ones discussed during Chapter 3, may prove more effective and efficient for this cooling application.

All of these questions posed above will help maintain the appropriate design for the cooling of artesian bore water. They are an integral part for the continuous improvement of this dynamic cooling application.

CHAPTER 8

CONCLUSIONS

8.0 Conclusions

8.1 Conclusions

The project has focused its research on the heat transfer mechanisms that are in action when cooling artesian bore water whilst submerged in water and also in air. It was discovered that conduction, convection and radiation are all contributing to this heat transfer as well as the evaporative cooling effect from the surface of the pond. Alternative water cooling techniques were investigated and discussed along with the fluid flow characteristics in pipelines.

The cooling grid design spreadsheet model was subjected to a sensitivity analysis to identify key variables and aid in the selection of alternative pipe materials for testing. The discussion of the physical properties of possible pipe material alternatives also aided in this selection which resulted in aluminium, copper and stainless steel being chosen for experimentation.

An experimental apparatus was then designed to test the performance of the selected pipe materials and heat transfer mediums. The experimental results were then analysed and used to compare the accuracy of the spreadsheet model to the actual measured results. Although exhibiting some discrepancies, the model was determined to be valid and accurate, whilst displaying some margin for error or factor of safety. Air as a heat transfer medium was deemed inappropriate from the experimental results because of the significant lack in heat transfer.

Using the experimental results, research and model validity as a background the alternative designs tested were comparatively analysed accounting for costs, cooling performance, pipeline flow characteristics, material availability, corrosion resistance and maintenance requirements. Aluminium was determined to exhibit the most desirable traits and was recommended as the most suitable alternative cooling grid pipe material.

Questions were then posed on the overall operating conditions for cooling grids and their necessity in future schemes. The need for continual improvement and research was highlighted to maintain the efficient and effective use of resources by the Department of Natural Resources and Water throughout Queensland.

8.2 Further Work

Future investigations into the results of this project would include the design and testing of a full sized aluminium cooling grid to empirically prove the project's outcomes and also to provide another comparison to the current copper cooling grid.

Alternative designs such as gas refrigeration and heat pipes could also be considered as completely different cooling systems and designed from scratch.

Temporary or transportable cooling grids also offer another area for future research to effectively consider the effects of the cooling bore head after capping and piping.

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APPENDIX A

Project Specification

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG 4111/4112 Research Project
PROJECT SPECIFICATION

FOR:	**ANDREW WATT**
TOPIC:	VALIDATION OF COOLING GRID MODEL AND TESTING OF ALTERNATIVES
SUPERVISORS:	Mr Joseph Foley Assoc Prof David Buttsworth Thomas Bean, Regional Manager, GABSI, DNR&W
SPONSORSHIP:	Department of Natural Resources and Water, Great Artesian Basin Sustainability Initiative
PROJECT AIM:	To predict and confirm the heat transfer parameters for cooling grids submerged in water ponds used for cooling artesian bore water, investigate other available options and validate/modify the design model to more accurately reflect existing operation.
PROGRAMME:	**Issue B, 16th October 2008**

1. Research material properties of alternate pipe materials, heat transfer mechanisms through air and water, alternative cooling techniques, flow characteristics and associated hydraulics theory for pipe networks.

2. Undertake sensitivity analysis of the spreadsheet design model to verify important variables to aid in pipe material selection.

3. Design a cooling grid test setup for on-site use and an experimental procedure to compare its performance using differing pipe materials to theoretical calculations from the existing spreadsheet design, test in field to compare the heat transfer characteristics in air and water using the selected pipe materials.

4. Comparatively analyse designs tested accounting for costs, material availability, flow characteristics at different flow rates, cooling performance and maintenance requirements.

5. Validate and calibrate the current DNR&W design spreadsheet using measured data, and make recommendations.

6. Write a dissertation and submit by 30/10/2008

AGREED: ___________________(student)____________________,___________________(supervisors)

____/____/2008 ____/____/2008 ____/____/2008

Examiner/Co-examiner__________________________________

APPENDIX B

Spreadsheet Model

Microsoft Excel Spreadsheet Model

INPUTS	SYMBOL	FORMULA	UNITS	VALUE
Peak Water Demand	Q	Should only be required to change values in blue squares	L/s	10
Inlet / Bore Temperature	Ti		^oC	57
Pressure Head at Inlet	P		m	31
Length of Individual Pipe	L_2		m	12.0
Required Outlet Temperature	To		^oC	40
Water Temperature of Pond	Tp		^oC	33
Inside Diameter of Pipe	Di		m	0.0167
Outside Diameter of Pipe	Do		m	0.0191
CONSTANTS	**SYMBOL**	**FORMULA**	**UNITS**	**VALUE**
Specific Heat of Water	Cw		J/kg.^oC	4180
Conduction Coefficient for Pipe Material	Kc		W/m.^oC	380
Conduction Coefficient for Water	Kw		W/m.^oC	0.56
Density of Water	ρ		kg/m^3	990
Kinematic Viscosity of Water	v	Calculated from graph	m^2/s	0.000000540
Fouling Factor for Water (>50^{o}C)	Rf		m^2.^{o}C/W	0
Coefficient of Roughness	k		m	0.000003
Pi	π		dimensionless	3.14159
CALCULATIONS	**SYMBOL**	**FORMULA**	**UNITS**	**VALUE**
Average Temperature in Grid	Ta	(Ti+To)/2	^oC	51
Inside Radius of Pipe	ri	Di / 2	m	0.0084
Outside Radius of Pipe	ro	Do / 2	m	0.0096
Calculation of Forced Convection HeatTransfer Coefficient				
Left Fluid Temperature Difference	ΔTa	Ti - Tp	^oC	24
Right Fluid Temperature Difference	ΔTb	To - Tp	^oC	12
Log-mean Temperature Difference	ΔT_{LM}	$\Delta Tb - \Delta Ta / \ln(\Delta Tb / \Delta Ta)$	^oC	17.3
Correction Factor	F	From Graph	dimensionless	1.0
Mean Temperature Difference	ΔT_{MEAN}	$\Delta T_{LM} * F$	^oC	17.3
Velocity in pipes	v	$((Q/1000)/((\pi*(Di^2))/4)/n)$	m/s	0.389
Reynold's Number in Pipes	Re	(Di * v) / v	dimensionless	12022
Prandtl Number in Pipes	Pr	Cw * v * ρ / Kw	dimensionless	3.99
Nusselt Number in Pipes	Nu	$0.023 * Re^{0.8} * Pr^{0.4}$	dimensionless	73.5

Heat Transfer Coefficient in Flowing Water	h1	(Nu * Kw) / Di	W/m^2.^{o}C	2464
Calculation of Natural Convection Heat Transfer Coefficient				
Mean Temperature for Natural Convection	Tm	(Ta+Tp)/2	^{o}C	42
Kinematic Viscosity for Natural Convection	*v*	Calculated from graph and Tm	m^2/s	0.000000 630
Volume Coefficient of Expansion for Water	*B*	Calculated from graph and Tm	m^3/^{o}C	0.000420 000
Grashof Number	Gr	(g*B*(Ta-Tp)Do^3)/*v*^{2}	dimensionless	1301996
Rayfield Number	Ra	Gr*Pr	dimensionless	5195496
C	C	Calculated from graph and Ra	dimensionless	0.48
n	n	Calculated from graph and Ra	dimensionless	0.25
Nusselt Number for Natural Convection	Nu	C*Ra^n	dimensionless	22.91648 427
Heat Transfer Coefficient in Still Water	hs	(Nu*Kw)/Do	W/m^2.^{o}C	671.8969 209
Modified Coefficient for Algal Growth	h2	60% * hs	W/m^2.^{o}C	403.1381 525
Calculation of Number of Pipes Required				
Heat Required To Be Lost to Pond	q	Q * Cw * ρ *(Ti - To)	W	496584
Overall Heat Transfer Coefficient	U	1 / ((1/h1) + Rf + (ri/Kc) ln (ro/ri) + ((ri/ro)*Rf)+(ri/(ro*h2)))	W/m^2.^{o}C	388
Area of Pipe Required	A	(q / (U * ΔT_{MEAN}))	m^2	73.93799
Total Length of Pipe Required	L	A / (π * Di)	m	1409.3
Trial Number of Pipes Required	n		dimensionless	117
Calculated Number of Pipes Required	n2	L / L_2	dimensionless	117
Difference between Trial and Calculated	Δn	n - n2	dimensionless	-0.00011
Frictional Loss Through Grid				
Pipe Friction Factor	f	0.0055[1 + ((20000*k)/Di) + (10^6/Re))$^{0.33}$]	dimensionless	0.029846
Frictional Loss Through Pipe	hf	((f * L_2 * v2)/(2*g*Di))*(1+(20/100))	m	0.198
Remaining head at outlet	Pt	P - hf	m	30.8

SUMMARY OF RESULTS

Length of Pipe Required	**1409.3**	**m**
Number of Pipes	**117**	**dimensionless**
Length of Each Pipe	**12.0**	**m**
Friction Loss Through Grid	**0.198**	**m**

APPENDIX C

Risk Assessment

Risk Assessment

ACTIVITY	HAZARD TYPE	RISK	LIKELIHOOD	CONTROL MEASURES
Manual Handling of Equipment	Lifting, Bending, Pushing, Pulling, Reaching	Back Injury, Sprains, Strains	Slight	- Use mechanical means where possible - Vary tasks between workers - Bend legs not back, hold close to body - Get assistance when possible - Report injuries
Vehicle Movement and Machinery	Motor Vehicle Accident, Rollover	Personal Injury, Death, Equipment Damage	Very Slight	- Inspect vehicles regularly - Drive to conditions - Obey road rules and speed limits - Utilise skilled drivers - Use observer to keep watch
Work performed near/in water bodies	Swimming, Slipping or Falling into water	Personal Injury, Death, Drowning	Slight	- Utilise skilled swimmers - Avoid slippery conditions - Maintain visual with observer
Working with high temperature water	Skin or Eye contact with hot water	Burns, Scalds, Loss of vision	Significant	- Wear proper personal protective equipment - Isolate working area from hot water when changing fittings etc
Remote Area Operations	Loss of Communication	Unable to call for assistance	Slight	- Inspect communication equipment regularly - Maintain call in times with base - Follow DNR&W Remote Area Operations Guidelines
	Vehicle Immobilisation or Isolation	Bogged, Break Down, Stranded	Significant	- Carry survival and first aid equipment - Carry vehicle recovery equipment shovel, winch, EPIRB, etc

APPENDIX D

Resources

Resources

All resources required for the completion of this project were supplied by the Department of Natural Resources and Water as per their sponsorship of the project. The resources that were utilised include:

- Copper, aluminium and stainless steel pipes purchased for testing by NR&W from relevant suppliers.
- EMS 050D data logger with temperature RTD PT100 probes of varying cable length currently owned by NR&W.
- Mercury thermometer.
- Digital thermometer.
- Wet and dry bulb thermometer, graduated cylinder and stopwatch borrowed from USQ engineering workshop.
- Transportation to testing site supplied by NR&W.
- Labour for testing and during experimentation supplied by the author and NR&W staff.
- Laptop computer for data logger recordings and calibration supplied by NR&W.
- Digital camera to obtain photographic evidence of testing and procedures supplied by NR&W.

Necessary steps have been taken to minimise costs involved for the project including, testing times, material acquisition and labour requirements. All purchases such as pipe material were made by DNR&W and arranged to be delivered in sufficient time. The critical items such as the data logger and pipe materials were inspected and tested prior to experimentation to ensure no in field failures.

APPENDIX E

Project Timeline

Project Timeline

Project Topic Allocation: 12th March 2008

Preliminary Research: March – May 2008

Project Specification: 25th March 2008

Sensitivity Analysis: April 2008

Experimental Procedure Design: April – June 2008

Project Appreciation: 26th May 2008

Continued Research: May – August 2008

Progress Assessment: 19th June 2008

Undertake Field Tests: July – August 2008

Results Interpretation, Model Validation and Begin Write-up: August 2008

Conclusions, Discussion and Project Conference: September 2008

Continue Write-up and Submit Draft Dissertation: September – October 2008

Submit Final Dissertation: 30th October 2008