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Impacts of chiller failure on temperature change in isolation incubators for salmonids

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ABSTRACT

Mechanical chillers can be used to slow the development of salmon eggs and fry. Chiller failure can result in a rapid temperature increases that may adversely impact salmon development. In this study, three types of chiller failure were simulated: (1) CF – failure of chiller, (2) PF – failure of recirculation pump, and (3) NR – chiller failure for a chiller system without a coldwater reservoir. Temperatures were monitored at 38 locations at the Burley Creek Hatchery using 4-channel loggers (Onset, Model U12-008) and Hobo pendant loggers (Onset, UA-001-64). The maximum temperature responses for 30-, 60-, and 90-min intervals were determined for both failure and restart. For the 30-min period, the maximum ΔTs were equal to 3.37 °C for NR, 2.62 °C for PF, and 1.79 °C for CF. The magnitude of the ΔTs were larger for restart compared to failure. The response of the Hobo loggers were very close to the 4-channel loggers even though their time response was significantly slower. The PF and CF failure modes were modeled as two unequal sized CFSTR (coldwater reservoir and incubator) in series and NR mode was modeled as a single CFSTR (incubator). Theoretical and measured mean hydraulic resident times were used to estimate the both deviation between the actual temperature and the modeled temperatures as well as the maximum temperature increases at 30-, 60-, and 90-min intervals. The PF-failure and NR-restart were quite good CFSTRs (stagnant regions of about 9%), while the remaining failure modes had poorer performance (stagnant regions ranging from 25 to 35%). If the theoretical mean hydraulic residence times are used for design, these values must be multiplied by the appropriate reactor correction factors to estimate the size of physical coldwater and glycol reservoirs needed.

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1. Introduction

It is often desirable in salmon hatcheries, to use pathogen free groundwater for incubations and early rearing. As groundwater is free of viruses, bacteria, and parasites it greatly improves fish health and survival and facilitates the transfer of fish between fish health management zones. In addition, the use of groundwater improves egg-hatching rates by eliminating extreme low temperature events typical of some surface waters (Poxton, 1991). Groundwaters are typically warmer than that of the ambient water temperature in salmon redds during most of the incubation period. This can have two important implications: (1) the ground water may be warmer than is optimal for egg development (Whitney et al., 2013), and (2) the warmer water will accelerate the development time of eggs and fry (Jensen et al., 2009). For unfed fry planting programs, early planting may result in starvation before natural food supplies develop in the spring (Roppel, 1982). For smolt programs, fish will grow larger than their wild counterparts, which may result in unnaturally high rates of early maturation and residualism (Healey et al., 2000).

Recent development in chiller technology has eliminated the need for a glycol loop. While these systems have reduced costs and footprints, temperature changes following chiller failure are much more rapid. Salmon hatcheries are often sited in remote areas with poor power quality and/or poor power reliability. While not adequately documented, hatchery staff has observed developmental problems in salmon fry following repeated chiller failures.

The purpose of this research is to determine the potential impacts of different chiller failure modes on changes in water temperature in isolation incubators commonly used in conservation hatcheries for salmonids. This information will be used to develop design models (based on chemical engineering reactor analysis) that can be used to estimate potential temperature changes over a

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Nomenclature

C_w	Heat capacity of water at constant pressure (J/kg °K)
C_g	Heat capacity of glycol/water mixture at constant pressure (J/kg °K)
P_g	Recirculating pump for glycol to heat exchanger
P_w	Recirculating pump for water to heat exchanger
Q_{system}	Flow from cold water reservoir to hatchery (Lpm)
Q_{incub}	Flow to individual incubator (Lpm)
SR	Stagnant regions expressed as a percent of reactor volume (%)
t	Time (minutes)
t_{90}	Time needed for temperature logger to achieve 90% of a step change in temperature (sec)
T	Temperature (°C)
T_{30min}	Maximum change in temperature over a 30 min period (°C) following chiller failure or restart
T_{60min}	Maximum change in temperature over a 60 min period (°C) following chiller failure or restart
T_{90min}	Maximum change in temperature over a 90 min period (°C) following chiller failure or restart
T^c_{30min}	Maximum acceptable change in temperature over a 30 min period (°C) following chiller failure or restart
T^c_{60min}	Maximum acceptable change in temperature over a 60 min period (°C) following chiller failure or restart
T^c_{90min}	Maximum acceptable change in temperature over a 90 min period (°C) following chiller failure or restart
T_{well}	Temperature of well or cold water supply (°C)
T_{cwr}	Temperature of cold water reservoir (°C)
T_g	Temperature of glycol reservoir (°C)
T_{final}	Final temperature of incubator over a failure/restart event (°C)
$T_{chilled}$	Design temperature for chilled conditions, measured in the incubators (°C)
T_{model}	Temperature computed from the models (°C)
V_{cwr}	Volume of cold water reservoir (L)
V^{design}_{cwr}	Volume of cold water reservoir (L) required for design
V_g	Volume of glycol reservoir (L)
V^{design}_g	Volume of glycol reservoir (L) required for design
V_i	Volume of individual incubator (L)
V^{eff}_{cwr}	Effective volume of cold water reservoir (L) based on Eq. (7)
τ_1	Theoretical mean hydraulic residence time of cold water reservoir, equal to V_{cwr}/Q_{system} or V^{eff}_{cwr}/Q_{system} (minute)
τ_2	Theoretical mean hydraulic residence time of incubator, equal to V_i/Q_{incub} (minute)
$\bar{\tau}_{c,1}$	Measured mean hydraulic residence of coldwater reservoir (minute) based on Eq. (3)
$\bar{\tau}_{c,2}$	Measured mean hydraulic residence of incubator (minute) based on Eq. (3)

wide range of biological and physical conditions and improve the overall quality of hatchery rearing programs for salmon.

2. Background

2.1. Impact of temperature on early development of salmonid

Biological development is a well-ordered series of chemical reactions that are controlled by temperature. Development can only take place within a narrow band of temperature, with temperatures outside of this range altering developmental success and egg and alevin survival. For sockeye salmon (*Oncorhynchus nerka*) incubated in constant 2.0°, 5.0°, 8.0°, 11.0°, or 14 °C water, those incubated at 8.0 °C had the highest survival (Murray and McPhail, 1988). Although egg survival was lower at both extremes, there was a greater decrease in survival at higher constant temperatures than lower constant temperatures. In areas with high ground water temperature chilling may be required to keep incubation temperatures within the proper range for high survival.

During the early stages of development salmon are most sensitive to physical changes in their environment. This is the "sensitive period" during which developing eggs should be treated with extreme care that protects them from mechanical shock and sheltered from light. Although, rarely considered, this is also a time when the developing eggs are probably also most sensitive to temperature changes that may desynchronize the chemical reactions required for normal development. Desynchronizing these biochemical reactions during early development may produce physical abnormalities or death. As with other physical factors, the developing embryo are less sensitive to rapid temperatures changes after the "eyed stage" when most major tissue differentiation has occurred.

The surface and ground water most hatcheries use for incubation normally exhibits very slow change in water temperature over the course of a day. In contrast, when hatcheries chill their incubation water very rapid (near instantaneous) changes in water temperature can occur following chill failure. The low variation in natural waters is exemplified by the temperature change observed near the site of sockeye salmon redds in Redfish Lake, Idaho during the January to April period (IDFW, 2013):

Maximum daily temperature change : 0.16–0.37 °C

Maximum hourly temperature change : 0.05–0.11 °C

Average hourly temperature change : 0.0001 to −0001 °C

It is known that rapid changes in incubation water temperature can result in abnormalities and death. When the eggs of Atlantic salmon (*Salmo salar*) were transferred from 6 °C to 12 °C water there was a significant increase in both vertebral deformities and mortality (Wargelius et al., 2005). The impacts of this temperature change were relatively constant over the development stage corresponding to 68–160 degree-days (day °C). Even slow lowering of incubation temperature from 7° to 3 °C during early development resulted in increased deformities and mortality in Arctic charr (*Salvelinus alpinus*) embryos (Jeuthe et al., 2015). At later stages of development, rapid temperature fluctuations between 3.5° and 6 °C did not affect the number of deformities or mortalities in this species. It is important to understand that most of these temperature studies were conducted with very small incubators that could be quickly moved from one water-bath to another. For these types of systems, the temperature change would be almost instantaneous. The closest experimental temperature exposures for chiller failure are thermal marking studies. Eggs and fry are repetitively exposed to ±3–4 °C temperature changes (Monk et al., 1993). These temperature changes have been found to have no impact on development or survival, but are typically used on eyed eggs or hatched fry (Volk et al., 1999).

2.2. Formulation of criteria for rapid temperature changes on fish

A temperature criterion for rapid temperature changes following chiller failure could be formulated in a variety ways. It could be based on a rate of change of temperature (dt/dT) or as a ΔT over a specific time period (such as 30 or 60 min). Alternatively, it could be based on the maximum ΔT over the entire failure event. It is also important to note that eggs are exposed to rapid temperature changes both following chiller failure and chiller restart.

2.3. Criteria for rapid temperature changes on fish

While literature on the impacts of temperature on salmonids is extensive, very little applies to the type of rapid temperature changes that result from chiller failure. Based on experience in Scottish hatcheries, Poxton (1991) suggested the maximum temperature change during incubation should be less than 1 °C per 24 h. Based on this review of the impacts of temperature on fish, the potential biological responses to temperature changes resulting from chiller failure may have the following characteristics:

1. Impacts may depend strongly on species and developmental stages.
2. The criteria may be formulated in terms of rate of change or total change.
3. The impacts may be different for rapid temperature increases and decreases but the relative impacts of the two are unknown at this time.

2.4. Provisional temperature criterion for this work

While the impact of constant temperature on the early develop of sockeye salmon is well know, limited information is currently available to support temperature criteria for temperature changes resulting from chiller failure. Therefore, for the purposes of this work, we shall select the following provisional criterion: ±1 °C over 30 min ($T^{c}_{30min} = \pm 1°C$). This criterion will be used to explore the impact of system temperature and reservoir volumes on chiller response, but should not be used for design purposes until additional information is available.

2.5. Characteristics of chiller

A chiller is a machine that removes heat from a liquid via a vapor-compression cycle. Chillers are typically rated in terms of tons where 1 ton = 12,000 BTU/hour (3.516 kW). The efficiency of chillers ranges from 0.5 to 1.5 kW/ton and depends strongly on size, duty cycle, type of cooling (air or water) and type of compressor.

Chillers for aquaculture applications typically range from 5 to 100 tons and are air- cooled. Compressors and circulating pumps are powered by 220 or 440 V three phase electrical power. Chilling for any significant flow requires a huge amount of energy. For example, chilling 400 Lpm by 5 °C would require 40 tons of chiller capacity and a power requirement ranging from 20 to 60 kW or $2200 to $6500/month at $0.15/kWh.

2.6. Type of chiller configurations

Chillers for aquaculture applications have evolved as their need developed and as a result, a number of different configurations are in use. Three of the most common configurations for incubation chilling are discussed below in order of their historical development:

2.6.1. Type 1 – chilled gas:glycol heat exchanger, glycol reservoir, glycol: water heat exchanger, coldwater reservoir, water → fish

This is the oldest type of chiller and uses a chilled gas-glycol heat exchanger within the chiller unit (Fig. 1A). The chiller circulates chilled propylene glycol (or ethylene glycol) to a glycol reservoir. Then chilled glycol and process water are pumped through a glycol-water heat exchanger; the chilled water returns to a chilled water reservoir and warmed glycol returns back to the glycol reservoir. The advantage of this type of system is the two reservoirs buffer changes in process water temperature and reduce cycling of the chiller compressor. Its disadvantage is increased capital and operating costs for the two reservoirs, two recirculation pumps, and a second heat exchanger. In addition, seal failure in the glycol/water heat exchanger can result in the release of glycol into the process water.

2.6.2. Type 2 – chilled gas:water heat exchanger, water → fish

This system is based on a more modern chiller design that uses a chilled gas:water heat exchanger within the chiller (Fig. 1B). The water flows directly through the chiller and to the fish. The advantage of this type of system is a reduced footprint and capital/operating costs. Its disadvantage is a greater chance of chiller heat exchanger freeze-up due to the higher freezing point of water and the lack of any reservoirs to buffer potential temperature changes.

2.6.3. Type 3 – chilled gas:water heat exchanger, coldwater reservoir, water → fish

This is a combination of Type 1 and Type 2 (Fig. 1C). It has lower capital/operating costs than Type 1 and increased temperature buffering compared to Type 2.

2.7. Chiller failure

The most serious type of chiller failure is failure of the chiller itself. This may result from (a) failure of the compressor, failure of the internal recirculating pumps, low refrigerant level, or freeze-up of the internal heat exchanger, (b) loss of station power, or (c) loss of the incubation water supply. Depending on the specific failure, the chiller might be down for several hours to weeks if major components need to be ordered, shipped, and replaced.

In the Types 1 and 3 systems, loss of recirculating pumps can occur. This is less serious than a general chiller failure, as replacement wet ends or motors are typically available from local sources. Replacement of a failed pump or motor may range from 1 to 2 h if spares are available onsite to 1–2 days if replacements must be purchased and shipped.

The most common type of chiller failure is due to temporary loss of station power or low voltage on one leg of the three-phase power supply. Many salmonid hatcheries are located in remote locations where loss of power and low voltage transients may be common. Modern chiller systems have sophisticated monitoring and alarm functions that can detect loss of power or low voltage for times as short as 15–30 ms. Once a low voltage condition has been detected and the low voltage alarm set, the chiller will shut down. If the normal voltage is restored, how the chiller responds depends on the programming. If the chiller is programmed to allow a restart, a 10–30 min restart procedure will be initiated. This time is needed to confirm system pressures and flows (refrigerant, glycol or water, lubricants), and time for the stop-to-start timer, reboot time, and chiller loading to be completed. For temperature-sensitive operations such as data centers, pharmaceutical, and manufacturing facilities requiring constant cooling, special modifications are available to reduce the time needed for chiller restart and re-establishment of the design chilled water temperature (Lin et al., 2016).

2.8. Modeling of temperature during chiller failure

The modeling of the temperature response during chiller failure and restart is based on chemical engineering reactor analysis. In this analysis, it will be assumed that (a) the glycol reservoir, cold-water reservoir, and incubators are ideal continuous-flow, stirred-tank reactors (CFSTRs), (b) the volume of the connecting pipes can be

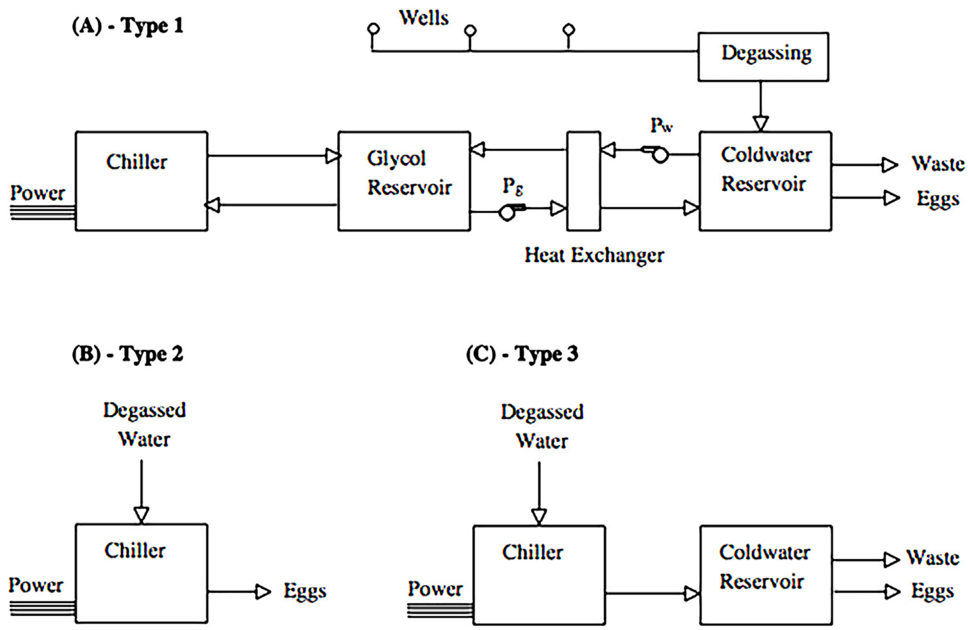

Fig. 1. Common types of chiller systems used in salmonid incubation systems. A. Older system with both glycol and coldwater reservoir; B. Newer system with chilled gas/water heat exchanger and no reservoirs; C. System B with coldwater reservoir. All of the chillers include an internal chilled gas/fluid heat exchanger.

ignored, and (3) heat transfer across the reservoirs and piping can be ignored. The validity of all of these assumptions will be tested with the collected experimental data.

The response of an ideal CFSTR is a function of the theoretical mean hydraulic resident time:

$$\tau = \frac{\text{Reactor Volume(L)}}{\text{Flowrate(Lpm)}} \quad (1)$$

A reactor could be any type of container such as a reservoir, rearing tank, or incubator. An ideal CFSTR reactor is well mixed and the effluent temperature is equal to the bulk temperature within the reactor.

For a real CFSTR, the mean hydraulic residence time ($\bar{\tau}_c$) for a step change from 0 to T_{max} (Levenspiel, 2012) can be computed from:

$$\bar{\tau}_c = \frac{\int_0^\infty (T_{max} - T)dt}{T_{max}} \quad (2)$$

or for discrete data

$$\bar{\tau}_c = \frac{\int_{j=1}^{n} (T_{max} - T)\Delta t}{T_{max}} \quad (3)$$

Where

T = Temperature (°C)

t = Time (s)

If, $\bar{\tau}_c \cong \tau$, the reactor is close to an ideal CFSTR. A $\bar{\tau}_c > \tau$ is physically impossible and is due to experimental measurement errors.

A $\bar{\tau}_c$ less than the theoretical residence time (τ) establishes the presence of stagnant regions (SR) within the reactor (Watten et al., 2000). The magnitude of the stagnant regions is commonly expressed as a fraction of the reactor volume:

$$SR = \left[\frac{V - V_c}{V}\right] = 1 - \frac{\bar{\tau}_c}{\tau} \quad (4)$$

Where

SR = Stagnant regions as fraction of the reactor volume (dimensionless)

V = Volume of reactor (L)

V_c = Volume of reactor computed from $\bar{\tau}_c$ Q (L)

$\bar{\tau}_c$ = Mean hydraulic resident time computed from Eq. (3) (min)

τ = Theoretical mean hydraulic resident time computed from V/Q (min)

Q = Flow to reactor (Lpm)

The tracer curves for some reactors have very long tails. In such cases, the tracer curve is commonly cut off at $3\bar{\tau}_c$(Levenspiel, 2012). The following models for Type 1 and 2 failures (Fig. 1A, B) are written in terms of the theoretical mean residence times (τ_1 and τ_2); they could be written equally as well in terms of the measured mean hydraulic residence time ($\bar{\tau}_{c,1}$ *and* $\bar{\tau}_{c,2}$).

If Eq. (4) is solved for V, the following relationship can be developed:

$$V = V_c\left[\frac{1}{1 - SR}\right] \quad (5)$$

The term within the bracket is the reactor correction factor. If the chiller design is based on theoretical hydraulic residence times (τ), the reactors volumes must be multiplied by the appropriate Reactor Correction Factor. If the chiller design is based on measured hydraulic residence times ($\bar{\tau}_c$), this factor is not needed.

2.8.1. Model, system type 2, failure mode: No reservoir-up (NR)

Since this system does not have a cold-water reservoir, it can be modeled as a single CFSTR and a step increase in temperature t = 0 (Levenspiel, 2012):

$$T = T_{chilled} + (T_{well} - T_{chilled})\left[1 - Exp(-t/\tau_2)\right] \quad (6)$$

Where

T = Temperature at any time (°C)

$T_{chilled}$ = Initial temperature (°C)

T_{well} = Temperature of well or water source (°C)

t = Time (minute)

τ_2 = Mean hydraulic residence time of incubator, equal to V_i/Q_{incub} (minute)

Table 1
Maximum ΔTs as a function time interval and failure mode (CF = chiller failure, PF = pump failure, NR = no reservoir, T1 & T3 = troughs 1 and 3, I1, I16, I17, and I32 = incubator location (see Fig. 1). Based on 4-channel logger placed at the bottom of the incubators.

		Failure (up)				Restart (down)			
Failure Mode	Location	30 min	60 min	90 min	Maximum	30 min	60 min	90 min	Maximum
CF(n = 6)	T1/I1&I17	1.84 ± 0.11	3.06 ± 0.16	3.78 ± 0.22	5.03 ± 0.33	−2.06 ± 0.08	−3.36 ± 0.13	−4.06 ± 0.16	−5.07 ± 0.08
	T1/I16&I32	1.75 ± 0.10	2.97 ± 0.18	3.69 ± 0.23	4.97 ± 0.37	−1.98 ± 0.13	−3.27 ± 0.15	−3.96 ± 0.16	−5.04 ± 0.06
	T3/I1&I17	1.80 ± 0.10	3.02 ± 0.17	3.74 ± 0.21	4.98 ± 0.31	−2.00 ± 0.08	−3.29 ± 0.13	−4.01 ± 0.15	−5.05 ± 0.08
	T3/I16&I32	1.77 ± 0.09	2.98 ± 0.17	3.70 ± 0.22	4.99 ± 0.34	−1.99 ± 0.07	−3.28 ± 0.10	−3.99 ± 0.15	−5.07 ± 0.06
PF(n = 4)	T1/I1&I17	2.69 ± 0.04	3.65 ± 0.04	3.96 ± 0.03	4.32 ± 0.02	−2.72 ± 0.01	−3.13 ± 0.02	−3.34 ± 0.02	−3.91 ± 0.17
	T1/I16&I32	2.57 ± 0.03	3.57 ± 0.03	3.90 ± 0.03	4.36 ± 0.03	−2.57 ± 0.04	−3.05 ± 0.02	−3.27 ± 0.03	−3.93 ± 0.20
	T3/I1&I17	2.64 ± 0.04	3.60 ± 0.02	3.91 ± 0.02	4.28 ± 0.02	−2.65 ± 0.03	−3.09 ± 0.02	−3.31 ± 0.02	−3.91 ± 0.18
	T3/I16&I32	2.57 ± 0.04	3.58 ± 0.03	3.90 ± 0.03	4.37 ± 0.02	−2.60 ± 0.01	−3.08 ± 0.02	−3.31 ± 0.02	−3.95 ± 0.21
NR(n = 6)	T1/I1&I17	3.27 ± 0.28	3.28 ± 0.29	3.28 ± 0.29	3.30 ± 0.30	−3.77 ± 0.22	−3.67 ± 0.18	−3.59 ± 0.16	−3.78 ± 0.23
	T1/I16&I32	3.54 ± 0.21	3.58 ± 0.22	3.58 ± 0.22	3.60 ± 0.23	−3.71 ± 0.22	−3.65 ± 0.18	−3.56 ± 0.15	−3.71 ± 0.21
	T3/I1&I17	3.07 ± 0.35	3.09 ± 0.35	3.08 ± 0.36	3.10 ± 0.36	−3.20 ± 0.27	−3.13 ± 0.25	−3.07 ± 0.24	−3.22 ± 0.26
	T3/I16&I32	3.60 ± 0.26	3.64 ± 0.27	3.64 ± 0.27	3.66 ± 0.27	−3.68 ± 0.21	−3.61 ± 0.17	−3.56 ± 0.13	−3.69 ± 0.20

V_i = Volume of incubator (L)
Q_{incub} = Flow to individual incubator (Lpm)
The value of T in Eq. (6) changes from $T_{chilled}$ (t = 0) to T_{well} at large values of t (t > 5τ).

2.8.2. Model, system type 1, failure mode: water pump failure – up (PF)

This system can be modeled as two CFSTRs of unequal volume in series (Hill and Hill, 1972; Lesson 4, 2006):

$$T = T_{chilled} + (T_{well} - T_{chilled})\left[1 - \frac{\tau_1}{\tau_1 - \tau_2}Exp(-t/\tau_1) + \frac{\tau_2}{\tau_1 - \tau_2}Exp(-t/\tau_2)\right] \quad (7)$$

Where
τ_1 = Mean hydraulic residence time of cold water reservoir, equal to V_{cwr}/Q_{system} (minute)
V_{cwr} = Volume of cold water reservoir (L)
Q_{system} = Flow from cold water reservoir (Lpm)

2.8.3. Model, system type 1, failure mode: chiller failure –up (CR)

This system is similar to the previous system in that it contain two CFSTRs in series but the effective volume of the cold water reservoir is equal to:

$$V_{cwr}^{eff} = V_{cwr} + \left[\frac{C_w T_{chilled}}{C_g T_g}\right] V_g \quad (8)$$

Where
C_w = Heat capacity of water at constant pressure (J/kg °K)
C_g = Heat capacity of glycol/water mixture at constant pressure (J/kg °K)
$T_{chilled}$ = Temperature of cold water reservoir (°C)
T_g = Temperature of glycol reservoir (°C)
V_g = Volume of glycol reservoir (L)
and

$$\tau_1 = V_{cwr}^{eff}/Q_{system} \quad (9)$$

2.8.4. Model, NR-down, PF-down, and CR-down

The model for chiller restart (down) is similar to failure (up), except, the term $T_{chilled} + (T_{well} - T_{chilled})$ should be replace with $T_{final} + (T_{chilled} - T_{final})$ in Eqs. (6) & (7).

3. Materials and methods

3.1. Facility information

Experimental work was conducted at the Burley Field Station, Port Orchard, Washington from September 1–15, 2015. This facility is used for freshwater rearing of sockeye salmon from Redfish Lake, Idaho. This stock has been listed as endangered under the Endangered Species Act (1973).

3.2. Chiller system

The chiller system consisted of a 6-ton mechanical chiller, a glycol reservoir, a cold-water reservoir, a plate and frame heat exchanger, and two circulating pumps (Fig. 1A). Detailed information on each unit is presented in Supplemental Table 1. Both well water and chilled water was provided to the incubation room.

3.3. Incubator and incubation systems

The incubation room (110 m^2) consisted of 15 troughs each containing 32 isolation incubators (Fig. 2). Water was distributed to the individual incubators from a 1.5" PVC pipe in the center of each trough, through threaded fittings and hose connections, through 180 mm length of clear plastic tubing, and into the incubators.

Each isolation incubator consisted of two 3.8L plastic buckets nested together. Two 13 mm holes were drilled on opposite sides of the bottom bucket, approximately 32 mm from the top of the bucket (Maynard et al., 2012). A 132 mm hole was cut out of the bottom of the upper bucket and black plastic netting glued over the hole. Two small wood spacers were added to the top bucket to elevate the upper bucket 20 mm above the bottom bucket. Eggs from a single female would be added to the upper bucket and the water flow for each incubator was directed into the top bucket. The incubator water flowed down through the incubator and eggs, across the space between the bottoms of the two buckets, up the annulus between the sides of the two buckets, out the two 13 mm holes into the trough, and out the trough drain.

3.4. Temperature loggers

Two types of temperature loggers (Onset Computer Corporation, Bourne, MA, USA) were used:

64k Hobo pendant logger, Model UA-001-64 (8 bit word)

4-channel external logger, Model U12-008 (12 bit word) with air/water/soil thermistor sensor, model TMC6-HD.

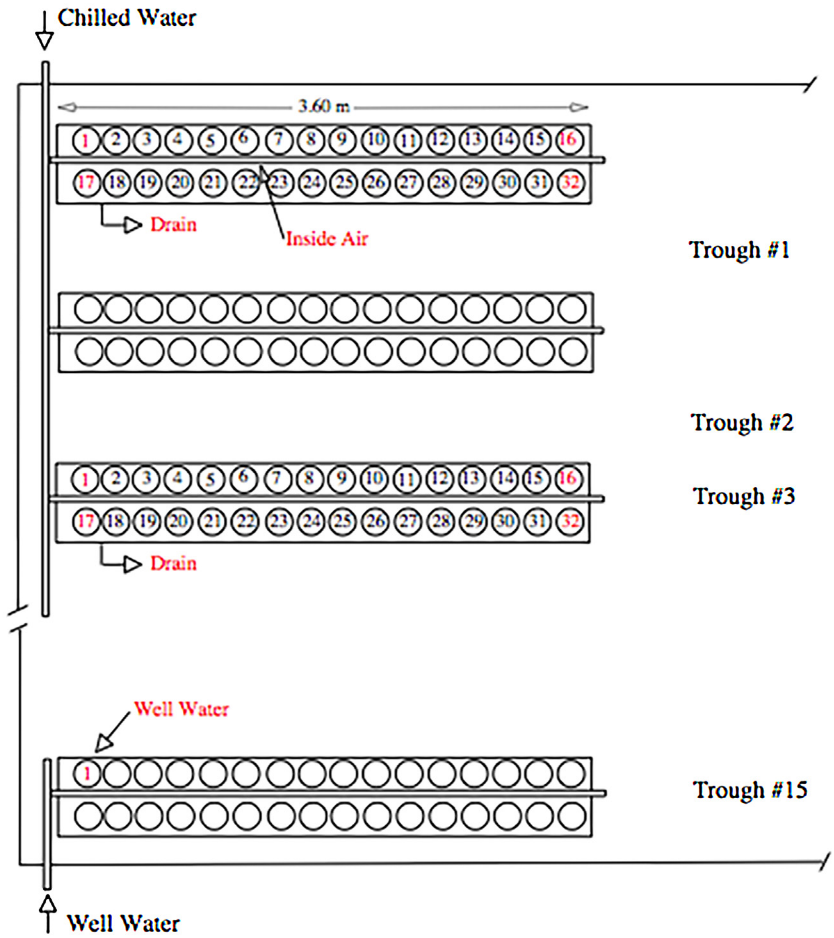

Fig. 2. Layout of chiller system at Burley Creek Hatchery, Port Orchard, Washington, USA. Temperature loggers were located in Trough 1 (incubators 1, 17, 16, and 32), Trough 3 (incubators 1, 17, 16, and 32), Trough 7 (incubator 1), The drains from Troughs 1 and 3, and the inside air.

The locations of the loggers are shown in Fig. 2 and Supplemental Table S-2. In this article, H refers to the Hobo pendent loggers and 4C to the 4 channel external logger. The temperature was logged every minute. Temperatures were monitored at 24 sites using a total of 38 temperature sensors. Capital "T" is used for temperatures and lower case "t" for time. Temperatures are report in degrees Celsius and time in minutes or seconds.

Both loggers use thermistor sensors. The thermistors for the 4 Channel units are encased in stainless cylinders (4 mm in diameter x 38 mm long) and connected to the logger by 2 m electrical cables. The thermistors for the Hobo loggers are inside a 30 mm by 50 mm plastic case that contains the electronics and battery.

3.5. Flow control and adjustment

For this work, chilled water was supplied to Troughs 1 and 3. Water flow to each trough was measured by use of a bucket and stopwatch. Water flows were measured at the start of each failure simulation series or when the flow was changed. Flows to each trough were adjusted to maintain a constant flow rate using a manometer installed on the influent end of each trough header.

3.6. Experimental work

3.6.1. Logger response

The time responses of the Hobo (n = 4) and 4-channel loggers were evaluated by transferring the thermistors from warm water to an ice bath. The ice bath was gently aerated to prevent stratification. The time to 90% response was computed by fitting a regression line to the temperature vs. time curve and solving for the time where the temperature is equal to 0.10($T_{initial}$ $-T_{final}$).

3.6.2. Chiller performance

The chiller performance was evaluated by changing the glycol temperature setting and measuring the average temperature of the well water and cold-water reservoir over a 24-h period and the system flow rate. The performance was expressed in terms of tons based on 12,000 BTU/hr of heat transferred. It was assumed that a 30% propylene glycol – water mixture (by volume) was used resulting in a relative heat capacity (C_g/C_w) at constant pressure of 0.935 (Engineering Toolbox, 2016).

3.6.3. Chiller failure

Three types of chiller failures were simulated:

Glycol reservoir/cold water reservoir system – chiller failure (CF, Fig.1A)

Glycol reservoir/cold water reservoir system – water recirculation pump failure (PF, Fig.1A)

No reservoir system – chiller failure (NR, Fig.1B)

Both the response during failure (temperature increase or up) and after chiller restart (temperature decrease or down) was studied. Chiller failure (CF) was simulated by quickly turning up the glycol temperature setting from 3 °C to 20 °C (up). Pump failure (PF) was simulated by turning off the water-recirculating pump. Chiller failure for the no reservoir system (NR) was simulated by simultaneously turning off the chilled water supply and turning on the well water supply to a given trough. Following a simulated failure, temperatures were recorded every minute at 24 sites for 200–700 min. Each type of failure was replicated 2–3 times. For the CF and PF simulations, chiller failure occurred at 8:00 am and chiller restart occurred at 8:00 pm

3.6.4. Temperature analysis

The raw data from the loggers (.hobo) was exported as.cvs files and saved as EXCEL .xlsx files for analysis. The temperature data from a given sensor type, location, and failure run was analyzed separately. For each dataset, the following parameters were computed:

3.6.4.1. Maximum ΔT for each 30-, 60-, and 90-min interval. Starting with $t = t_0$ (failure), the ΔT corresponding to $t_0 + 30$, $t_0 + 60$, and $t_0 + 90$ min were determined. Then, the ΔT for the three intervals was determined each sequential time interval. The largest ΔT for the entire dataset was determined (T_{30min}, T_{60min}, and T_{90min}). This analysis was needed because the maximum ΔT for a given failure mode may not occur immediately following the failure ($t = t_0$).

3.6.4.2. Time to achieve a 1, 2, 3, or 4 °C temperature change. Each dataset was transformed by subtracting out the initial temperature. The time corresponding to a 1, 2, 3, or 4 °C temperature change was based on the time nearest the required temperature change.

3.6.4.3. Theoretical mean hydraulic residence times (τ). Based on the measured flows (Supplemental Table S3) and measured volumes (Supplemental Table S4), the theoretical residence times for the coldwater reservoir and incubator were computed using Eqs. (1), (7), and (8). Based on measured volumes and flows, the mean hydraulic residence times were estimated for the piping between (a) the coldwater reservoir and the incubator room, (b) incubator room and the start of the distribution header for Trough #1, (c) incubator room and the start of the distribution header for Trough #3, and (d) between sequential discharges to the individual incubators (Supplemental Table S5).

3.6.4.4. Computed mean hydraulic residence times ($\bar{\tau}_c$). Based on Eq. (3), the computed mean hydraulic residence times were computed for each experimental run. In addition, the stagnant regions were estimated for each run using Eq. (4).

3.6.4.5. Reactor modeling. Based on the appropriate model (Eqs. (5)–(8)), the modeled temperature for each failure mode was computed for both the theoretical and measured mean hydraulic residence times. The standard deviation between the model and actual data was computed for each run. In addition, the deviation between model and actual data was determined at 30, 60, and 90 min.

3.6.4.6. Chiller system design modeling. Based on the computed mean hydraulic residence times (Eq. (3)) and Eqs. (6) and (7), the temperature changes for the three failure modes were computed for 30-, 60-, and 90-min as a function of volume of coldwater reservoir.

3.7. Statistical analysis

Statistical differences between means were determined by 2-way analysis of variance using R (R. Foundation, 2015), version

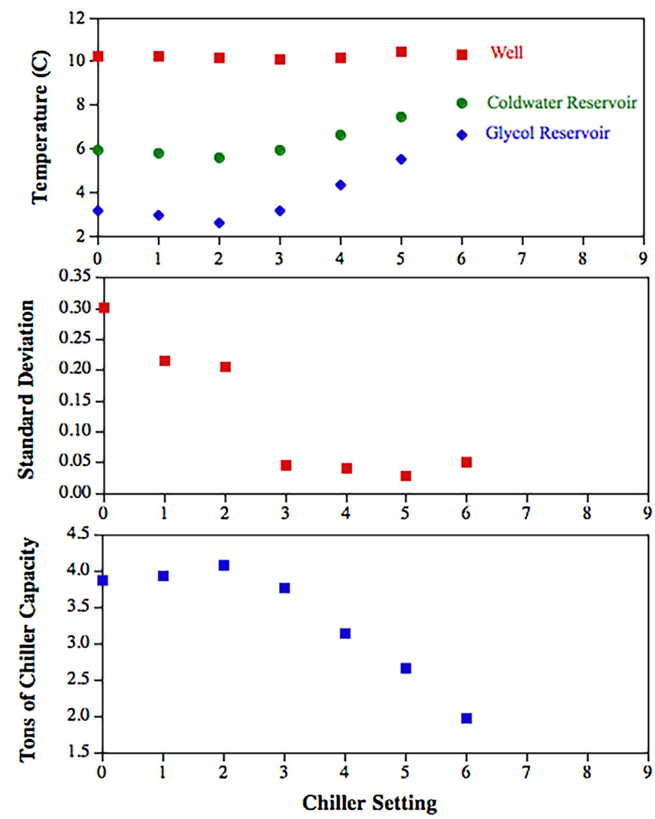

Fig. 3. Chiller performance as a function of glycol chiller setting. A. Temperature of well, glycol reservoir, and water reservoir; B. Standard deviation of water reservoir temperatures; C. Chiller capacity (1 ton = 12,000 BTU/hr = 3.516 kW).

3.02 at $P < 0.05$. When significant differences occurred, significance between individual means were tested using Tukey HSD at $P < 0.05$.

4. Results

For the chiller failure work, 38 temperature sensors were used. Eight failure runs were conducted and each one included both failure and recovery temperature responses, resulting in 608 individual datasets. This study generated a huge amount of data (15 Mb of temperature data and 60 Mb of analysis files). To reduce the amount of data to be presented, this work will focus on the following:

1. 4-Channel temperature loggers, Troughs 1 and 3, and bottom sensor locations. The 4-Channel logger records temperature information as a 12-bit measurement vs. 8-bits for the Hobo. The bottom sensor is closest to where the eggs will be located and therefore is the most relevant location.
2. The first 120 min following failure and restart.
3. Specific information on (a) top vs. bottom sensor locations, (b) 4-Channel vs. Hobo logger comparisons, and (c) Trough 1 vs. Trough 3 differences will be presented within a biological context.

4.1. Logger response

The 4-Channel sensors responded much more rapidly ($t_{90} = 20 \pm 3$ s) than the Hobo sensors ($t_{90} = 305 \pm 13$ s).

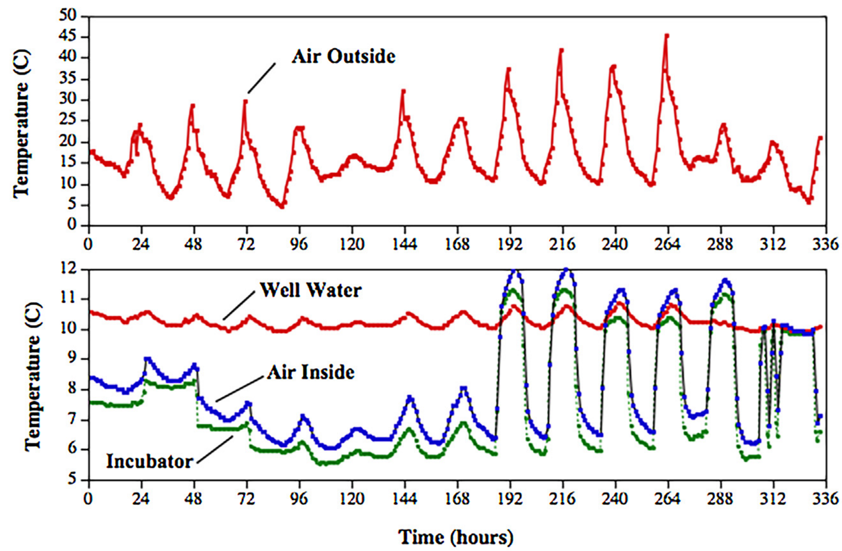

Fig. 4. Air and water temperatures during September 1 to September 15, 2015. A. Outdoor air temperature, B. Indoor air temperature, well temperature, and incubator temperature.

4.2. Chiller performance

Lowering the chiller glycol temperature setting (T_g) from 6 °C to 2 °C lowered both the glycol reservoir and coldwater reservoir temperatures (Fig. 3A); at lower settings the glycol and coldwater temperature increased slightly. For T_g temperature lower than 3 °C, temperature variation significantly increased (Fig. 3B). The maximum chiller capacity was 4.09 tons at T_g = 2 °C. (Fig. 3C). Based on both chiller capacity and temperature variability, all of the following chiller failure work was conducted with T_g = 3 °C.

4.3. Chiller failure

4.3.1. Ambient conditions

The variation in well, outdoor air, indoor air, Trough 1/Incubator 1 temperatures for the experimental period is presented in Fig. 4. The indoor temperatures were driven by the incubation water, especially after September 8 when the chiller failure work was conducted. While the well water temperature appears to be relatively constant in this figure (10.25 ± 0.21 °C), the diel variation in the well water as it enters the incubation room ranged from 0.20 to 0.88 °C (mean = 0.63 °C).

4.3.2. Representative temperature changes for the chiller failure modes

Representative changes (n = 1) in temperature for the three chiller failure modes are presented in Fig. 5A for both failure and recovery. More detailed information is presented in Fig. 5B for failure and in Fig. 5C for recovery. It appears that there is a major difference in the responses between the failure modes and for CF and PF and temperatures higher than the well water temperature are produced during chiller failure events.

4.3.3. Maximum ΔT for 30-, 60-, and 90-min intervals

While there were no statistical significant differences in temperature between the locations (Incubators 1, 17, 16 and 32) or between Troughs 1 and 3, there were consistent trends for chiller failure (CF) and pump failure (PF). Within a trough (start – end), the maximum temperature changes were always less at the ends for failure and greater for restart (Table 1). The same trends were evident between troughs and for the overall incubator system. The response of the no reservoir (NR) were highly variable between troughs and the changes in many cases were opposite of what was observed for the other two failure modes.

Table 2
Grand means for failure modes and time to maximum ΔT. Based on 4-channel loggers, bottom location, and all loggers in Troughs 1 and 3. Means with different superscripts are significantly different (lower case for failure modes within columns and upper case for times within rows).

A. Chiller Failure (up)			
Failure Mode	Maximum ΔT for:		
	30 min	60 min	90 min
CF (n = 24)	^{a}1.79 ± 0.10^A	^{a}3.01 ± 0.16^B	^{a}3.73 ± 0.21^C
PF (n = 16)	^{b}2.62 ± 0.34^A	^{b}3.60 ± 0.35^B	^{a}3.92 ± 0.35^C
NR (n = 24)	^{c}3.37 ± 0.34^A	^{b}3.40 ± 0.35^A	^{b}3.39 ± 0.35^A

B. Chiller Restart (down)			
Failure Mode	Maximum ΔT for:		
	30 min	60 min	90 min
CF (n = 24)	^{a}-2.00 ± 0.09^A	^{a}-3.30 ± 0.12^B	^{a}-4.01 ± 0.15^C
PF (n = 16)	^{b}-2.63 ± 0.31^A	^{a}-3.09 ± 0.29^B	^{b}-3.30 ± 0.28^B
NR (n = 24)	^{c}-3.59 ± 0.31^A	^{b}-3.51 ± 0.29^A	^{b}-3.44 ± 0.28^A

Detailed information on the maximum ΔT for 30-, 60-, and 90-min intervals are presented as a function of failure mode (CF, PF, and NR) in Table 2 for the pooled data for all locations. The ΔTs statistical significantly increased with increasing time for CF and PF. The values of ΔTs for NR were not statistical significantly different with time. There was a statistical significant difference between the failure modes for the 30 min intervals with NR > PF >CF (Table 2). The differences between the failure modes became less pronounced at 60 and 90 min.

4.3.4. Time to 1, 2, 3, and 4 °C temperature changes

As with the maximum ΔTs, there were no statistical significant differences between the locations or troughs and the data for each failure mode were pooled. Within a failure mode, there was a significant difference in times for the 1, 2, 3, and 4 °C changes (Table 3). The fastest response was for NR followed by PF and cf. At the larger ΔTs, the differences between the failure mode were smaller and in most cases, not statistical significant.

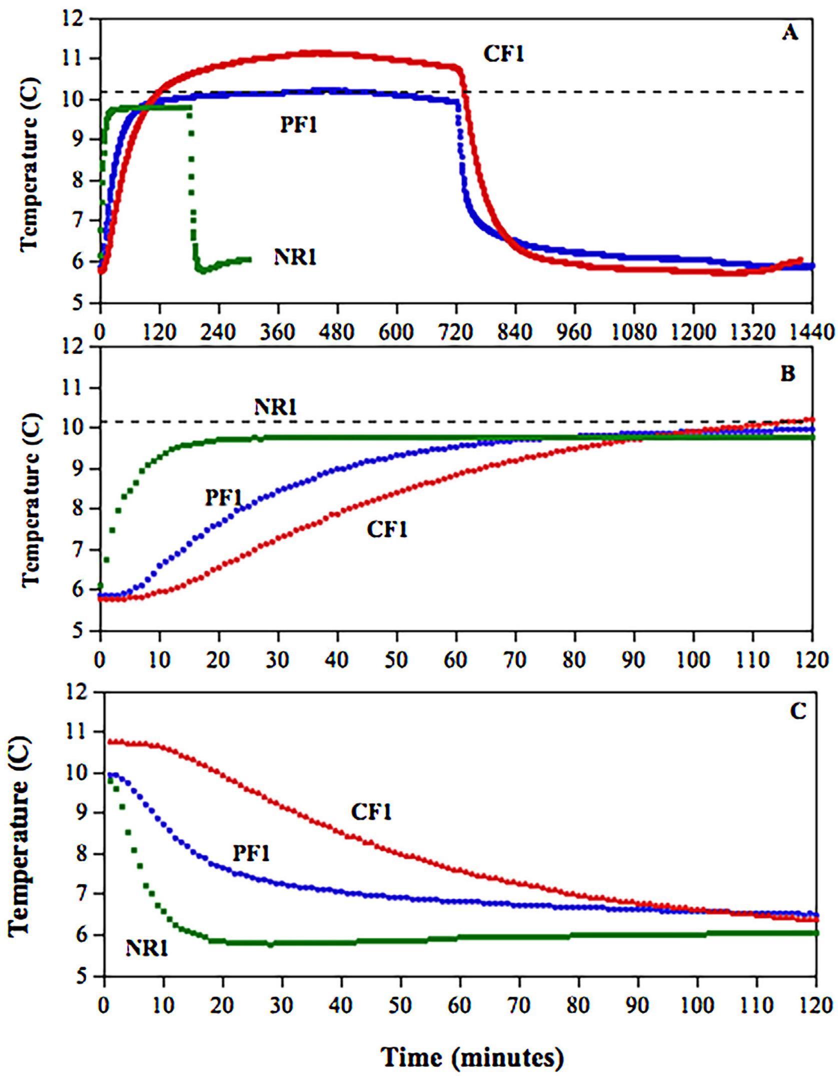

Fig. 5. Representative temperature variation as a function of chiller failure mode and time. A. Temperature variation during 720 min following failure and restart; B. Temperature variation during the first 120 min after chiller failure; C. Temperature variation during the first 120 min after chiller restart. (Based on a single run, Trough 1, Incubator 1, 4-channel logger, bottom location; CF = chiller failure, PF = pump failure, and NR = no reservoir).

Table 3
Grand means for failure modes and time to 1, 2, 3, and 4 °C. Based on 4-channel loggers, bottom location, and all loggers in Troughs 1 and 3. Means with different superscripts are significantly different (lower case for failure modes within columns and upper case for times within rows).

A. Chiller Failure (up)				
Failure Mode	Time to:			
	T = +1 °C	T = +2 °C	T = +3 °C	T = +4 °C
CF (n = 24)	$^{a}23.2 \pm 3.2^{A}$	$^{a}39.8 \pm 3.8^{B}$	$^{a}64.0 \pm 6.2^{C}$	$^{a}116.3 \pm 23.6^{D}$
PF (n = 16)	$^{ab}13.8 \pm 1.1^{A}$	$^{a}23.9 \pm 1.3^{AD}$	$^{c}40.7 \pm 1.8^{BD}$	$^{a}113.9 \pm 13.8^{C}$
NR (n = 24)	$^{b}2.4 \pm 0.6^{A}$	$^{b}4.6 \pm 1.0^{D}$	$^{bc}31.2 \pm 41.2^{C}$	$^{a}120.0 \pm 0.0^{B}$

B. Chiller Restart (down)				
Failure Mode	Time to:			
	T = −1 °C	T = −2 °C	T = −3 °C	T = −4 °C
CF (n = 24)	$^{a}22.8 \pm 1.2^{A}$	$^{a}37.1 \pm 1.8^{AD}$	$^{a}57.1 \pm 3.0^{CD}$	$^{a}95.2 \pm 9.1^{B}$
PF (n = 16)	$^{ab}8.9 \pm 1.3^{A}$	$^{a}16.9 \pm 1.5^{A}$	$^{c}52.1 \pm 3.7^{C}$	$^{a}620.3 \pm 78.8^{D}$
NR (n = 24)	$^{b}3.0 \pm 0.7^{A}$	$^{b}5.6 \pm 0.8^{A}$	$^{bc}15.8 \pm 22.3^{A}$	$^{a}116.0 \pm 19.0^{B}$

4.3.5. *Differences in temperature changes between hobo and 4-Channel loggers*

The differences in maximum ΔTs for the Hobo and 4-channel loggers are compared in Table 4 for Trough #1, Incubators 1 and 17, bottom locations. There were no differences between the two loggers. Typically, the differences between the loggers were within ±1%, except for "NR up" where the difference was 12%.

4.3.6. *Differences between the top and bottom locations*

For Trough 1, Incubators 1 & 17, and a single failure event, the mean difference between the top and bottom locations for the first 120 min ranged from +0.030 to +0.038 °C for the 4-Channel logger and from 0.034 to −0.066 °C for the Hobo loggers. The largest difference occurred in the no reservoir option and ranged from 0.5 to 0.7 °C for failure and from −0.5 to −0.6 °C for restart.

4.4. *Reactor response*

The computed mean hydraulic resident times ($\bar{\tau}_c$) for chiller failure, pump failure, and no reservoir modes are presented in Table 5. It was necessary to cut off the tracer curve at 20 min for the NR-down runs because the temperature started to increase for two of the replicates (see Section 2.8 for truncation criterion). The stagnant regions for each of the failure modes were computed from Eq. (4) using $\bar{\tau}_c$ (Table 6) and τ (Supplemental Table S4). The stagnant regions (SRs) ranged from 9 to 35%. PF-up and NR-down had the

Table 4
Comparison of maximum ΔTsfor 4-Channel and Hobo loggers as a function of time interval and failure mode. Based on trough 1, incubators 1 &, 17 and bottom locations.

		Failure (up)				Restart (down)			
Logger	Failure Mode	30 min	60 min	90 min	Maximum	30 min	60 min	90 min	Maximum
4-Channel	CF (n = 6)	1.84 ± 0.11	3.06 ± 0.16	3.78 ± 0.22	5.03 ± 0.33	−2.06 ± 0.08	−3.36 ± 0.13	−4.06 ± 0.16	−5.07 ± 0.08
	PF (n = 4)	2.69 ± 0.04	3.65 ± 0.04	3.96 ± 0.03	4.32 ± 0.02	−2.72 ± 0.01	−3.13 ± 0.02	−3.34 ± 0.02	−3.91 ± 0.17
	NR (n = 6)	3.27 ± 0.28	3.28 ± 0.29	3.28 ± 0.29	3.30 ± 0.30	−3.77 ± 0.22	−3.67 ± 0.18	−3.59 ± 0.16	−3.78 ± 0.23
Hobo	CF (n = 6)	1.81 ± 0.09	3.09 ± 0.17	3.80 ± 0.19	5.08 ± 0.38	−2.07 ± 0.09	−3.38 ± 0.12	−4.09 ± 0.16	−5.10 ± 0.08
	PF (n = 4)	2.67 ± 0.06	3.65 ± 0.06	3.97 ± 0.05	4.39 ± 0.11	−2.73 ± 0.06	−3.16 ± 0.05	−3.36 ± 0.05	−3.95 ± 0.18
	NR (n = 6)	3.65 ± 0.28	3.68 ± 0.30	3.68 ± 0.30	3.68 ± 0.30	−3.82 ± 0.22	−3.75 ± 0.17	−3.63 ± 0.14	−3.82 ± 0.22
Percent Difference in Means									
	CF	−1%	1%	0%	1%	1%	1%	1%	1%
	PF	−1%	0%	0%	2%	0%	1%	1%	1%
	NR	12%	12%	12%	12%	1%	2%	1%	1%

Table 5
Mean Residence Time for Reactors (Levenspiel, 2012).

Reactor (Mode)		Time Period	Chiller Failure (up)				Chiller Restart (down)			
			Rep #1	Rep #2	Rep #3	$\bar{X} \pm SD$	Rep #1	Rep #2	Rep #3	$\bar{X} \pm SD$
V_{cwr}^{eff}	(CF)	120 min	43.30	39.84	43.69	42.28 ± 2.12	40.8	40.20	41.07	40.69 ± 0.45
V_{cwr}	(PF)	120 min	25.01	25.51	N/A	25.26 ± 0.36	17.12	18.84	N/A	17.98 ± 1.22
V_i	(NR)	120 min	5.33	5.41	5.20	5.31 ± 0.10	2.09[1]	5.48	−2.67[1]	1.63 ± 4.09
V_i	(NR)	25 min	4.91	4.82	5.32	5.02 ± 0.27	6.32	5.91	5.78	6.00 ± 0.28
V_i	(NR)	20 min	4.37	4.15	4.60	4.37 ± 0.22	5.57	5.21	5.34	5.37 ± 0.19

[1] The temperature for these two runs rapidly approach a temperature close to $T_{chilled}$ and then started to increase potentially due to heat transfer.

lowest stagnant regions. The rest of the failure modes had SRs in the range of high 20%s to high 30%s. The reactor correction factor (Eq. (5)) ranged from 1.09 to 1.55.

4.5. Design model accuracy

Based on the design equations (Eqs. (6)–(8)), the modeled temperatures were computed for both τ and $\bar{\tau}_c$ values. Representative information on the differences between the actual temperature and those predicted from the τ and $\bar{\tau}_c$ values are presented in Fig. 6. For each failure, the standard deviations between the modeled temperature and actual temperatures as well as the temperature deviations at 30-, 60-, and 90-min are presented in Table 7. As expected, the standard deviations were lower when the $\bar{\tau}_c$ values were used. The maximum deviations for $\bar{\tau}_c$ ranged from 0.02 to 0.14 °C for up and 0.00–0.38 °C for down. A positive deviation is more serious as it represents an under-estimation of the modeled temperature change.

4.6. Design modeling

The no reservoir option does not contain a coldwater reservoir (Fig. 7A), so the volume of coldwater reservoir has no impact. The volume of the coldwater reservoir had a major impact on the temperature variation for the chiller failure (Fig. 7B) and for pump failure (Fig. 7C). For provisional temperature criterion = +1 °C in 30 min, the required theoretical volume of the coldwater reservoir would be about 2800 L for chiller failure and about 4900 L for pump failure. These computations were based on a fixed glycol reservoir volume and $T_{chilled}$ equal to 777 L and 5 °C, respectively.

5. Discussion

5.1. Chiller performance

Down to a glycol temperature setting of 3, the chiller system at Burley Creek Hatchery maintained the temperature in the coldwater reservoir very accurately (Fig. 3B). Below this setting, the coldwater reservoir temperature slightly decreased then started to increase. Between a glycol settings of 0–2, the variability of the temperature in the coldwater reservoir increased. Periodic variation in the coldwater reservoir temperature due to the defrost cycle (Mitz et al., 2014) was not observed.

5.2. Simulation procedures vs. actual failure

The accuracy of the simulations presented in the work may be different for the failure modes. It is important to note that all of these simulations assume that the un-chilled water continues to flow during the chiller failures. If this is not the case, significant or total mortality may result from a gradual increase in temperature, dissolved oxygen depletion, or the build-up of ammonia. Rapid increase in temperature is not a problem under these conditions.

The pump failure (PF) mode was simulated by turning the pump off for 12 h and then turning it back on. This is very close to what would happen in real pump failure if personnel and a replacement pump were available. If personnel and a replacement pump were not available, much longer failure times would result.

The chiller failure (CF) mode is similar to what might happen during an electrical power failure. If the failure is result of actual chiller failure, then the chiller may not be restarted for days to

Table 6
Stagnant regions (SR) and design safety factor as a function of failure mode. The reactor correction factor is equal to 1/(1-SR(%)).

Failure Mode	Chiller Failure (up)		Chiller Restart (down)	
	SR(%)	Correction Factor	SR(%)	Correction Factor
Chiller Failure (CF)	[a,d]31.2 ± 3.4	1.45	[a]28.9 ± 8.6	1.41
Pump Failure (PF)	[b]9.2 ± 1.3	1.10	[a]35.4 ± 4.4	1.55
No Reservoir (NR)	[c,d]25.5 ± 3.8	1.34	[b]8.5 ± 3.2	1.09

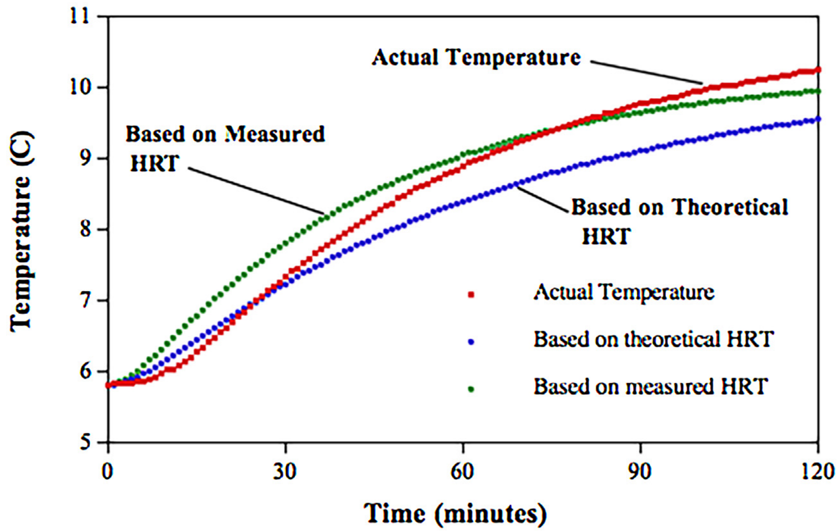

Fig. 6. Representative model results based on theoretical (Supplemental Table S4) and computed mean hydraulic residence time (Table 5) for pump failure (n = 1).

Table 7
Comparison of the temperature deviation of the model results (actual temperature (T)– computed temperature (T_{model})) as a function of theoretical and measured hydraulic detentions times. Based on 4 channel loggers, Trough 1, and the mean of incubators 1 & 17).

Failure/Mode	Based on Theoretical Detention Time (τ)				Based on Measured Detention Time ($\bar{\tau}_c$)			
		Deviation (°C)				Deviation (°C)		
	SD	30 min	60 min	90 min	SD	30 min	60 min	90 min
CF-1/up	0.486	0.096	0.499	0.663	0.294	−0.477	−0.150	0.121
CF-2/up	0.552	0.434	0.627	0.657	0.133	−0.116	0.004	0.135
CF-3/up	0.445	0.109	0.470	0.603	0.248	−0.389	−0.094	0.131
CF-1/down	0.320	−0.033	−0.332	−0.419	0.211	0.288	0.023	−0.139
CF-2/down	0.324	−0.022	−0.340	−0.445	0.206	0.284	−0.001	−0.177
CF-3/down	0.345	0.040	−0.320	−0.467	0.252	0.375	0.050	−0.174
PF-1/up	0.172	0.269	0.193	0.106	0.057	0.020	0.053	0.042
PF-2/up	0.157	0.247	0.160	0.103	0.052	0.001	0.022	0.040
PF-1/down	0.475	−0.759	−0.176	−0.045	0.240	−0.200	0.155	0.094
PF-2/down	0.485	−0.764	−0.203	−0.071	0.239	−0.203	0.129	0.069
NR-1/up	0.092	−0.003	−0.012	0.000	0.022	−0.020	−0.012	0.000
NR-2/up	0.095	−0.004	0.000	−0.012	0.030	−0.021	0.000	−0.012
NR-3/up	0.052	0.030	0.013	0.013	0.043	0.016	0.013	0.013
NR-1/down	0.186	−0.277	−0.127	−0.051	0.177	−0.269	−0.127	−0.051
NR −2/down	0.063	−0.058	−0.013	0.000	0.056	−0.050	−0.013	0.000
NR −3/down	0.319	−0.441	−0.280	−0.127	0.303	−0.433	−0.280	−0.127

weeks depending on what failed. This failure mode was simulated by turning up the glycol temperature setting to >20 °C (rather than turning the chiller off) and then turning the glycol temperature back to 3 °C for restart. This approach was selected because repeatedly cycling a chilling on and off is not recommended. The restart simulation may over-estimate the temperature change because the chilling capacity following an actual restart may not approach final capacity for 30–90 min.

The no reservoir mode (NR) is the least accurate of simulations tested. This simulation was produced by simultaneously turning off the chilled water supply and turning on the well water supply at the individual trough the two valves were less than 0.6 m from the start of the trough distribution header. In a real NR system, there could be more chilled mass (heat exchanger and distribution piping) to slow the change in temperature.

5.3. Impact of failure mode on the rate of temperature change

The rate of temperature change can be described in terms of the temperature change over a given time period (Table 2) or the time required to reach a given $\pm\Delta T$ (Table 3). Immediately following failure, the most rapid changes in temperature are for NR followed by PF and CF. Over longer intervals (or higher ΔTs), there is little difference between the three failure modes as the maximum temperature change is function of T_{well} and $T_{chilled}$.

5.4. Impact of failure mode on the maximum temperature change

The impact of failure mode on the maximum temperature change is exactly the reverse (CF > PF > NR) from the impact on the rate of temperature change. At times greater than approximately 120 min, the subsequent change in temperature is likely to be due to heat transfer from the air to water and direct absorption of solar energy on chiller components. The amount of solar radiation absorbed will depend on time of day, cloud cover, time of year, orientation and color of surfaces, and surface area of the various exposed components. The heat transfer to the water will depend on air temperature, physical properties of the piping and reservoirs, and local weather conditions. The lowest maximum temperature variation was for the NR failure, although the impact of solar heating on the well water temperature was evident (Figs. 4 and 5A) and is a result of heat transfer on the degassing tower, head tank, and exposed piping common to all the failure modes tested. The maximum temperature increase for the PF mode was slightly higher, a

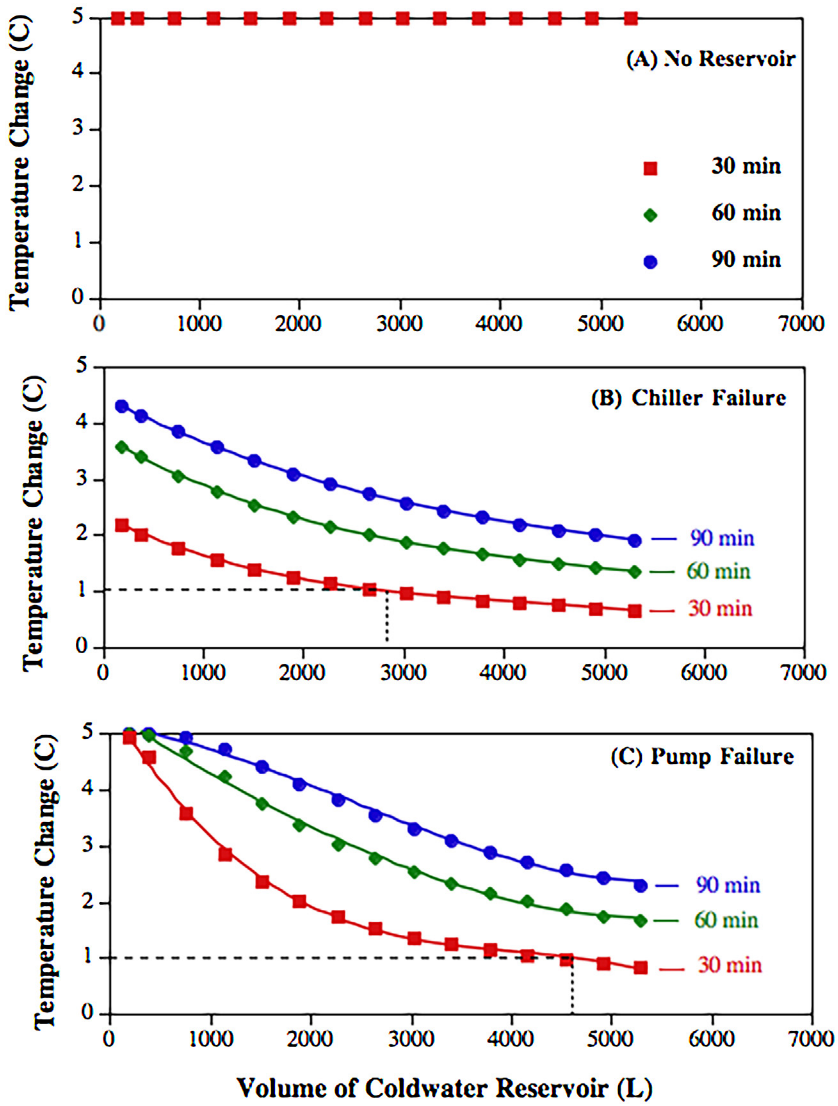

Fig. 7. Impact of the volume of coldwater reservoir on temperature rise (chiller failure). (Based on V_{cwr} ranging from 200 to 5,300L, V_g = 777 L, V_i = 3.46 L, C_g = 0.95, Q_i = 0.60 Lpm, T_{well} = 10 °C, and $T_{chilled}$ = 5 °C).

reflection of the small area of the coldwater reservoir and distribution piping. The largest temperature increase occurred with the CF mode and is related to the large area and volume of exposed components (glycol reservoir, circulating pumps/piping, and the coldwater reservoir).

Another thermal load to the chiller system are the two recirculating pumps (Fig. 1A). Based on the nameplate power and an assumed 70% efficiency, these pumps convert 2.98 kW of electrical power to 2.09 kW of fluid power. Within the piping system and heat exchanger, all of this fluid power is converted to heat. Assuming that all the heat contributed from the fluid power is retained in the chiller system, this load accounts for 16% of the overall chiller output (3.77 tons at a chiller setting = 3 °C). Accurate sizing of recirculation components (pumps, piping, and heat exchanger) and regular heat exchanger cleaning can help minimize this chiller load.

The very high air temperatures (>30 °C) are likely to be result of direct solar radiation on the temperature logger (Fig. 4). If chilling was required for locations and times with reduced solar radiation and air temperatures < well temperature, a decrease in water temperature may occur following chiller failure.

5.5. Differences between 4-Channel and hobo loggers

While the 4-channel logger is more accurate and has a faster response than the Hobo loggers, the Hobo loggers give essentially the same results for this type of chiller failure analysis (Table 4). This is useful because the Hobo logger is less expensive than the 4-channel logger and much more commonly available within fisheries agencies.

5.6. Validity of analysis assumptions

5.6.1. Well-mixed assumption

Based on the magnitude of the stagnant regions (Table 6), PF-up and NR-down were quite good CFSTRs. The other failure modes were less well mixed with SR ranging from 26 to 35%.

The temperature difference between the top and bottom of the individual incubators depended on the rate of temperature change (and therefore was larger for NR) and the type of logger. The water at the top of the incubator was typically warmer than the bottom upon failure and colder at the top upon restart.

The difference between the top and bottom for the Hobo loggers was larger than for the 4-Channel logger. This may be related to the fact that the upper Hobo logger was unsecured or due to the slower time response of this type of logger. The difference between the top and bottom of the incubators is probably not biological important even if the changes are statistically significant.

5.6.2. Impact of piping volumes

Between the chilled water distribution point inside the incubator room and the start of the distribution headers, the hydraulic resident times were only 26 s for Trough 1 and 11 s for Trough 3 (Supplemental Table S5). The hydraulic resident time for the incubator header ranged from 0.62 s for Incubator 1–13 s for Incubator 16. These times are small compare to HRT for the reservoirs and incubators and their impact on temperature will be small for this chiller system.

The assumption that these volumes can be ignored may not be valid for all chiller systems. The water within the piping volume is not well mixed and cannot be modeled as a CFSTR but is commonly modeled as plug flow with dispersion (Levenspiel, 2012).

5.6.3. No heat transfer assumption

This is not a bad assumption if the biological criterion is based on the maximum rate of temperature change over 0–120 min. This is a poor assumption if the biological criterion is based on maximum temperature change during the failure event. The potential impact of heat transfer on temperature change following chiller failure (or restart) is going to strongly depend on the characteristics of the specific physical chiller system, air temperature, solar radiation, and orientation of the components – something very difficult to accurately estimate. For systems where this may be important, it may be necessary to monitor the variation of temperature in the incubators with the chillers off. It is important to note that for the Burley Creek Hatchery, up to 20% of the chiller capacity was being used to remove heat that had been added to the well water. Insulation of piping, reservoirs, and other exposed components as well as construction of radiation shielding may significantly reduce capital and operational costs of chiller systems.

Within the incubators and troughs, the maximum temperature changes were reduced as the water flowed down the incubator headers or between troughs (Table 1, CF and PF). These changes were small and not statistically or biologically significant. The highly variable differences between troughs for the NR option are probably due to variations in how the chilled and well water valves were operated. The differences in response between CF and PF and NR may have resulted from the very rapid temperature changes for this failure mode and the way the maximum temperature values were computed.

5.7. Chiller design

Based on theoretical hydraulic resident times and Eqs. (6)–(8), reasonable valves of the 30-, 60-, and 90-min maximum temperature changes can be estimated for the three failure modes. While more accurate estimates can be computed from the measured $\bar{\tau}_{1,c} + \bar{\tau}_{2,c}$, these values cannot be measured until the system has been built. Therefore, once the required V_{cwr} and V_g have been determined, the design values ($V_{cwr}^{design} + V_g^{design}$) can be computed by multiplying V_{cwr} and V_g by their respective reactor correction factors (Table 5). How the reactor correction factors determined in this work applies to other incubator systems is not known at this time.

The impact of V_{cwr} (for a fixed value of V_g) on temperature change at 30-, 60-, and 90-min is presented in Fig. 7. For a provisional criterion of +1 °C, the required V_{cwr} ranges from 2800 L for CF to 4900 L for PF. These values were based on a fixed value of V_g = 777 L. Note that response of CF depends on both the values of V_{cwr} and V_g while the response of PF only depends on V_{cwr}. The response of NR depends on neither V_{cwr} and V_g, only V_i. While it might be possible to adjust the volume of the incubators to reduce temperature change, the requirement for large numbers of isolation incubators makes this infeasible.

The actual volume of the coldwater reservoir needed for design depends on both the estimated volume in Fig. 7 and the Reactor Correction Factor (Table 6):

Mode	Failure (up)			Restart (down)		
	V_{cwr}	RCF	V_{cwr}^{design}	V_{cwr}	RCF	V_{cwr}^{design}
CF	2800	1.45	4100	3800	1.41	5400
PF	4900	1.10	5400	4200	1.55	6500

The required volume for the coldwater reservoir on restart is 20–30% higher than for failure for a 1 °C temperature change in 30 min.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.aquaeng.2017.01.002.

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