Aquacultural Engineering 76 (2017) 20–33

Contents lists available at ScienceDirect

Aquacultural Engineering

journal homepage: www.elsevier.com/locate/aqua-online

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

John Colt*, Desmond Maynard

Environmental and Fisheries Sciences Division, Northwest Fisheries Science Center National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 2725 Montlake Blvd. East, Seattle, WA 98112, United States

ARTICLE INFO

Article history:
Received 11 August 2016
Received in revised form 27 December 2016
Accepted 16 January 2017
Available online 22 January 2017

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.

Published by Elsevier B.V.

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

* Corresponding author.
E-mail address: john.colt@noaa.gov (J. Colt).

http://dx.doi.org/10.1016/j.aquaeng.2017.01.002
0144-8609/Published by Elsevier B.V.

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