

# DESIGN AND FIELD DEMONSTRATION OF A HIGH EFFICIENCY HEAT RECLAIM SYSTEM WITH HEAT PUMP IN A NORTHERN PISCICULTURE

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## ABSTRACT

Conventional salmonid culture processes in northern fish farms sometimes require oil- or natural gas-based water heating systems to improve productivity, and this in the context of a continually increasing cost of fossil fuels and environmental constraints. This paper presents a thermodynamic/mechanical development project and a six-month field demonstration of a heat-reclaim system including an original, custom-made water-to-water heat pump and a passive heat exchanger installed in an existing fish-farming facility in Canada, in order to eliminate fossil fuels and thus improve the environmental performance of such systems. The purpose of the heat reclaim system was to heat fresh, cold water used in salmonid culture by using the energy recovered from the waste water. The system's energy balance was achieved from several thermodynamic parameters measured and/or calculated during two consecutive, 3-month production cycles (temperature, pressure, enthalpy and flow rate for both water and refrigerant sides, electrical power and energy, etc.). A data acquisition program with a long-distance data transmission system and a complete data computing software were developed for this particular study. A simultaneous collection of breeding data also allowed to establish a precise production balance and to determine the alevin production cost. Significant savings in industrial production and energy operating costs in a cold climate ultimately resulted in a very short pay-back period of the initial capital investment.

## 1. INTRODUCTION

Salmonid culture intended for the breeding, consumption and sport-fishing markets is in full growth in Canada. Generally, northern fisheries companies use fresh, relatively cold water directly in incubation and fish nursery units, without any preliminary heating (Morin 1996). However, preheating the water would promote accelerated alevins growth and could be highly profitable for producers. Generally, conventional systems include a water inlet with oxygenation columns, a plate heat reclaim heat exchanger, a water rotary filter and pumps, and, occasionally, an oil-burning water-preheating device. An advanced, highly efficient heat recovery system, including a water-to-water heat pump that uses low temperature waste water (below 10°C) as a heat source, was developed and then field-tested (Minea 1998). This aquacultural heat recovery system was installed in an existing, modern fish farm (**Figure 1.1**) and then extensively instrumented to determine its suitability for other fisheries or similar applications for eliminating any fossil fuel and/or direct electrical heating. The system's energy balance was computed in real time from several measured thermodynamic parameters during two consecutive 3-month production periods. A simultaneous collection of breeding data also permitted the establishment of a precise production balance and the calculation of the actual cost of sac fry production (Champagne 1998). The main objective of the heat recovery system was to reduce energy consumption and costs, as well as to increase

productivity of a particular industrial process by transferring energy between two closely located waste and fresh water streams.



Figure 1.1 – View of the Fish Farm Building

**2. PROCESS AND HEAT-RECLAIM APPROACH**

The fish nursery is the initial stage of the fish farming production cycle which leads to the production of young fish. The fry-rearing process begins when the eggs hatch and ends after about three months, when the fish reach a weight of about 5 grams or a length of 7,5 cm. For every cycle, several hundreds of thousands of impregnated eggs are placed in incubation baskets where the water temperature is generally maintained at 6 to 8°C until hatching. For incubation, water temperature is the most determinant factor because the length of the process period is inversely proportional to the water temperature (Figure 2.1). The water temperature at the beginning of the alevin’s rearing process is also important because it activates the fish’s metabolism and digestion, and stimulates the sac fry to eat more frequently and in greater quantities. Alevin’s size also increases with both the oxygen saturation ratio and water-flow velocity. The fish nursery unit used for this experiment was composed of several breeding water pools with a total volume of 45 m<sup>3</sup>, where the total water-flow rate was approximately 21 L/s, of which about 50% represented fresh groundwater. The system (Figure 2.2) comprises a two-stage heat-reclaim process. First, about 10,5 L/s of fresh groundwater is directly pumped from deep ground wells through a conventional plate heat exchanger, which raises the water temperature by recovering energy from an almost equal flow of waste water coming from the fish breeding pools. Then, the fresh water is directed through the heat pump’s condenser where it is heated once again by the refrigerant, which also recovers heat from the waste water at the outlet of the passive heat exchanger. Thus, the water-to-water heat pump uses waste water as a heat source and groundwater as a sink. Finally, the warmer fresh water is directed through a conventional oxygenation system where it mixes with the re-circulated water-flow before returning to the alevin’s pools. Waste water is expelled into a special underground tank and then to a small river, without any pollution. The direct expansion heat pump (Figure 2.3) uses a HCFC-22 refrigerant and includes, among others,

three parallel unequal scroll compressors equipped with suction pressure control. The evaporator and the condenser are very compact water-to-refrigerant plate heat exchangers.

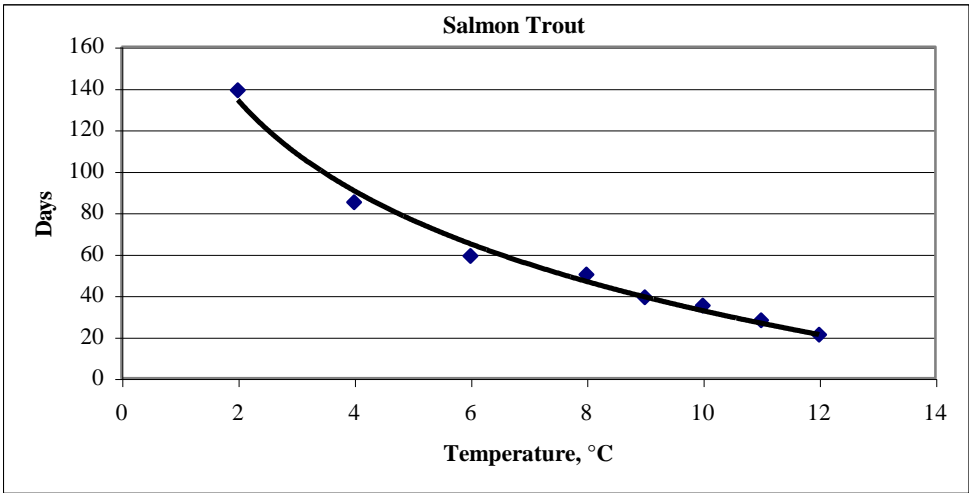


Figure 2.1 – Days Required for 50% Salmonid Hatching at Constant Incubation Temperatures (Champagne 1998)

The primary benefits of using a heat recovery heat pump are its flexible installation and simple controls. This is because the two closely located water streams have approximately the same flow rate and because of the possibility of performing a part-load operation by adjusting the number of compressors to the actual heating demand. In order to prove that the water-to-water heat pump is able to efficiently use a low-temperature heat source, to measure the seasonal energy performance of the entire system, and to establish an aquacultural, fully electric heating technology suitable for cold climates, approximately 45 parameters (temperature, pressure, flow rate, electrical power, operating state, etc.) were measured. Scanned four times per minute and recorded every two minutes, these parameters allowed to calculate the instantaneous and average energy balances for each particular component, as well as for the whole system. A data acquisition system, equipped with an HP 75000 unit with hard disk and modem allowed to collect and forward data daily to a central computer, where software especially designed for this application continuously processed the transferred data. The energy computations were carried out on both the refrigerant thermodynamic cycle and on the water-flow. The thermodynamic properties of the refrigerant (liquid density, vapour pressure, heat capacity, equation of state) were calculated using a subroutine based on a well-known method (Martin et al. 1955). The thermal efficiency of the passive heat exchanger was calculated with a simplified formula since the mass flow rate of both water streams are practically equal:

$$e = [(T_c - T_a)/(T_e - T_a)]*100 \quad (\%),$$

where  $T_c$  and  $T_a$  are, respectively, the groundwater outlet and inlet temperatures, and  $T_e$  is the waste water outlet temperature (°C).

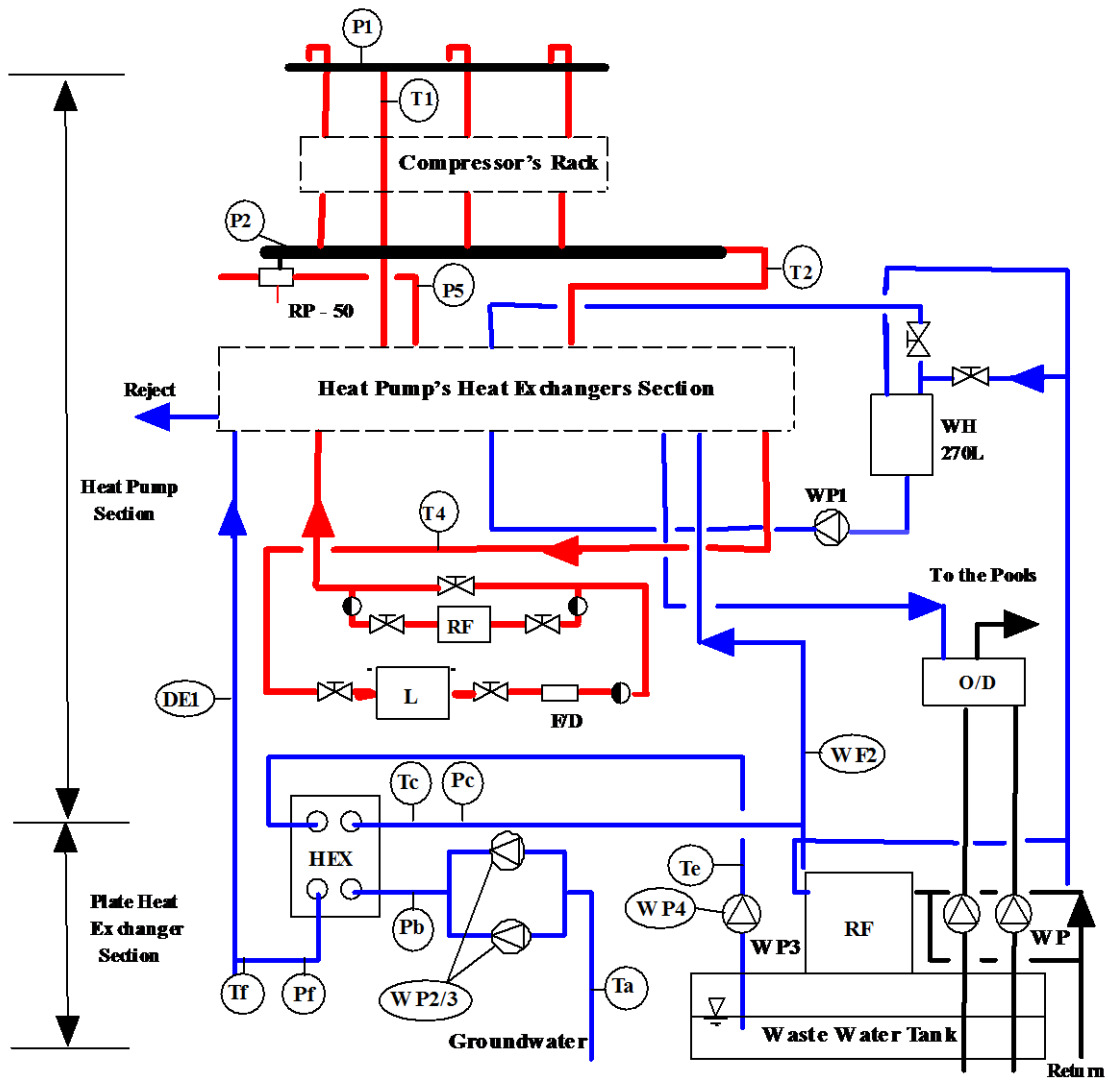


Figure 2.2 – Schematic Diagram of the Heat Reclaim System and Instrumentation  
T = temperature; P = pressure; W = power ;HEX = plate heat exchanger;  
DE/RF = water/refrigerant flow-meter

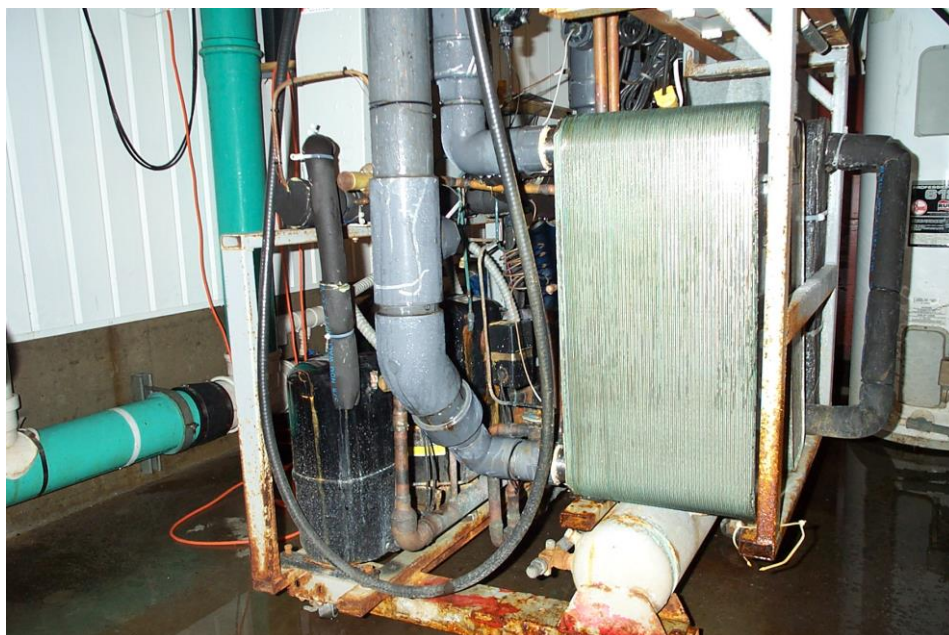


Figure 2.3 –View of the Heat Pump Heat Recovery Section

### 3. DISCUSSION

During each of the two, 3-month production cycles, the heat reclaim heating system operated about 99% of the time, a very good behaviour, generally allowing to optimize the pay-back period of such industrial heat reclaim systems. A few interruptions, averaging once every two weeks, were however necessary to properly clean the plate heat exchanger. Indeed, the decrease in thermal efficiency of this component, caused notably by deposits of insufficient filtered impurities on both heat transfer surfaces of the passive heat exchanger, required its periodic, manual cleaning: at the beginning with pure, pressurised cold water, and later by using appropriate chemical solutions. The average temperature of groundwater entering the system slightly decreased from 7,4°C in October to about 6,8°C in March, a normal but relatively negligible seasonal variation. On the other hand, as above-mentioned, the relatively sharp temperature variations in groundwater leaving the heat exchanger were due to undesirable animal impurities clogging the heat exchanger. Using cold water instead of hot, as expected, for the daily cleaning of the rotary filter, further dirtied the plate heat exchanger. This was why the average temperature of groundwater leaving the heat pump decreased from 11,9°C to about 10°C between two consecutive cleanings (Figure 3.1), and why a better chemical technique, using a phosphoric solution (6%) on the groundwater side, and a caustic soda solution (17 g/L) on the waste water side, was developed. Thus, the proper operating periods were prolonged from one to more than two weeks (Figure 3.2). On the other hand, the monthly average temperature of waste water entering the passive exchanger (heat source) remained around 11°C, with a slight decrease toward the end of the production cycle.

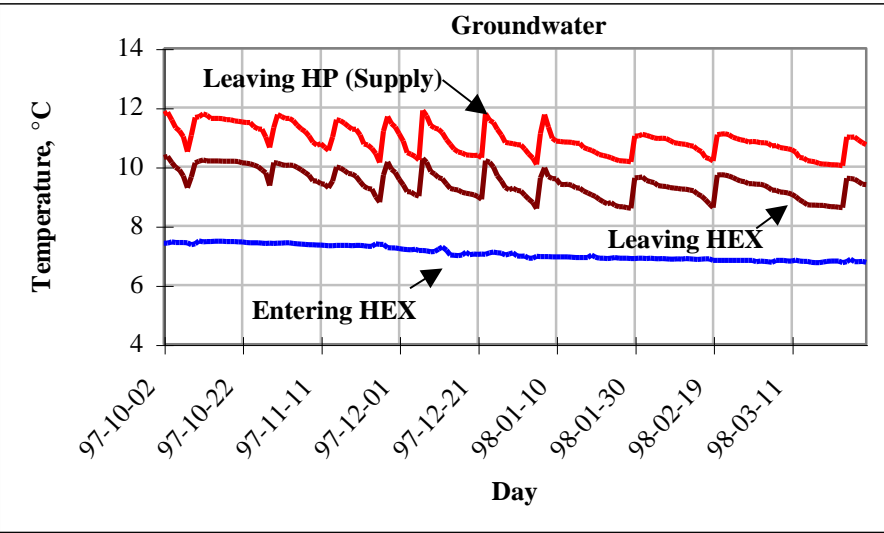


Figure 3.1 – Groundwater Monthly Average Temperature Profile

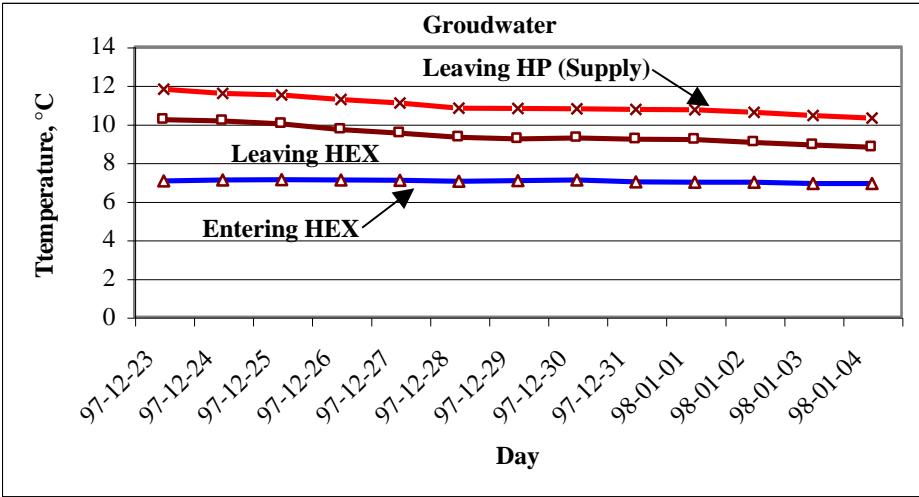


Figure 3.2 – Groundwater Temperature Profile between Two Consecutive Cleaning Operations

The monthly average heat pump parameters allowed to represent a typical thermodynamic cycle since the unit had operated under very stable conditions, with very low fluctuations, except for a few short periods for passive heat exchanger maintenance, although this took no more than 15 minutes every week or two (Figure 3.3). So, the heat pump functioned under steady conditions, which resulted in a high performance with practically any maintenance cost. The average compression ratio of the hermetic scroll compressors hovered around 1,6, mainly because of the slight temperature increase between the hot and cold energy sources, and also because of similar water stream flow rates.

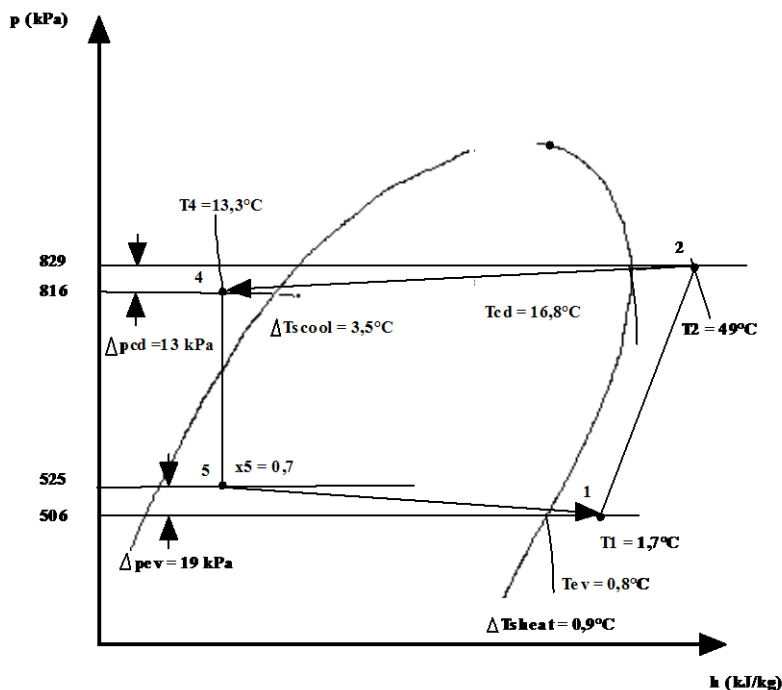


Figure 3.3 – Average Heat Pump's Thermodynamic Cycle

The heat pump operated with almost no suction superheating ( $0,9^\circ\text{C}$ ), and the discharge temperature never rose above  $60^\circ\text{C}$  (Figure 3.4). The controlled average evaporation temperature ( $0,8^\circ\text{C}$ ) prevented all time the evaporator freezing, while the average condensation temperature was  $16,8^\circ\text{C}$  (Figure 3.5). The condensation temperature, relatively low as compared to conventional systems, minimised electrical energy consumption. The absence of frequent on-off operating cycles and the low compression ratio will certainly help to increase the long-term technical life of the compressors. The average condenser subcooling ( $3,5^\circ\text{C}$ ) and the average refrigerant mass flow rate varied according to the actual heating load, directly influenced by water-flow fluctuations, which were in turn caused by the periodic presence of impurities in the heat exchanger. The heat pump's coefficient of performance (COP) (Figure 3.6) hovered around 6,1. In spite of the compact construction, the average evaporator and condenser refrigerant pressure losses were moderate (19 and 13 kPa, respectively).



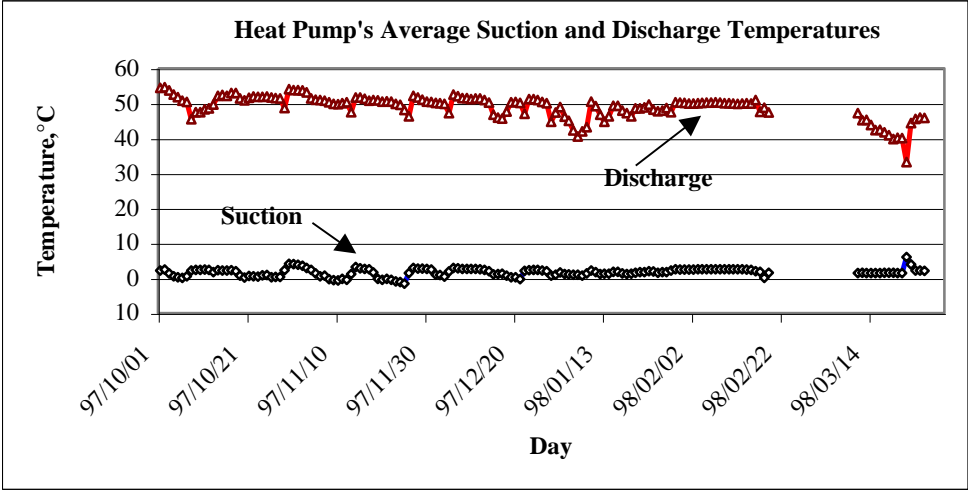


Figure 3.4 – Average Heat Pump’s Suction and Discharge Temperatures

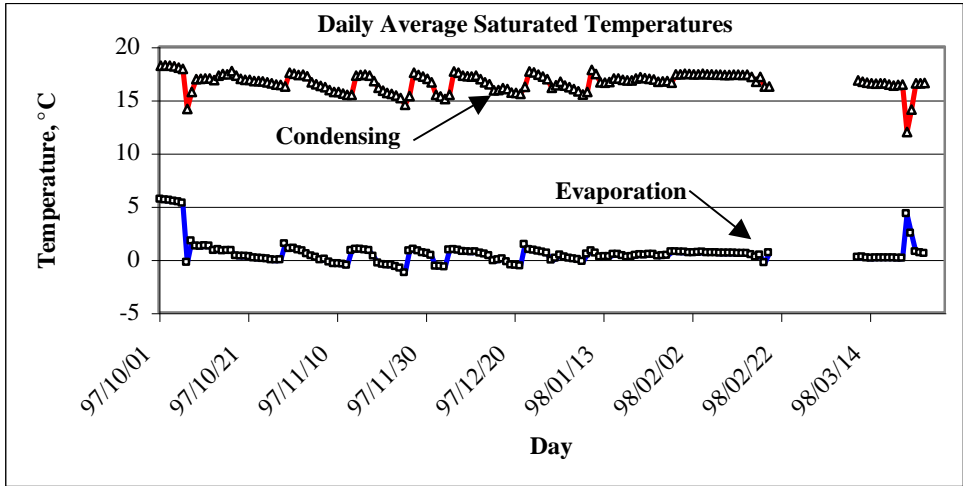


Figure 3.5 – Daily Average Condensation and Evaporation Temperatures

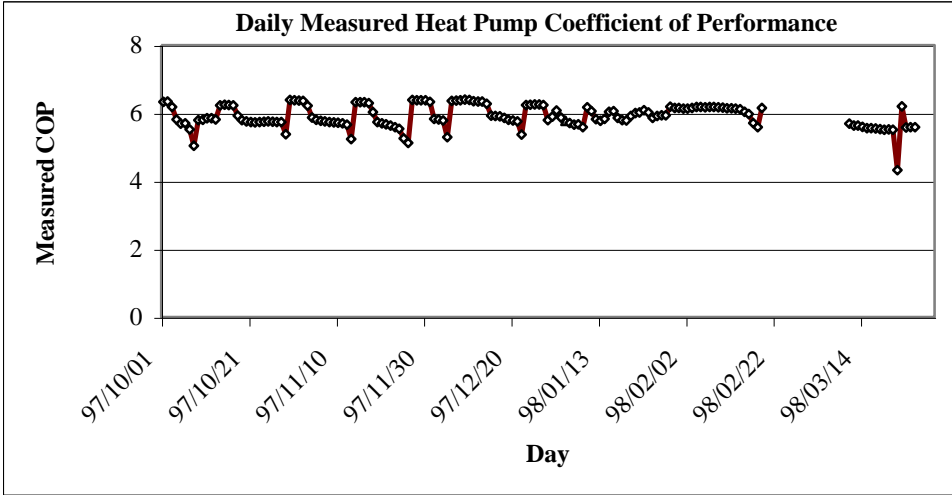


Figure 3.6 – Daily Average Heat Pump’s Coefficient of Performance



During the two consecutive, 3-month production periods, the heat pump consumed about 42 700 kWh, which corresponds to a shaft-measured average electrical power of 9,85 kW (Figure 3.7).

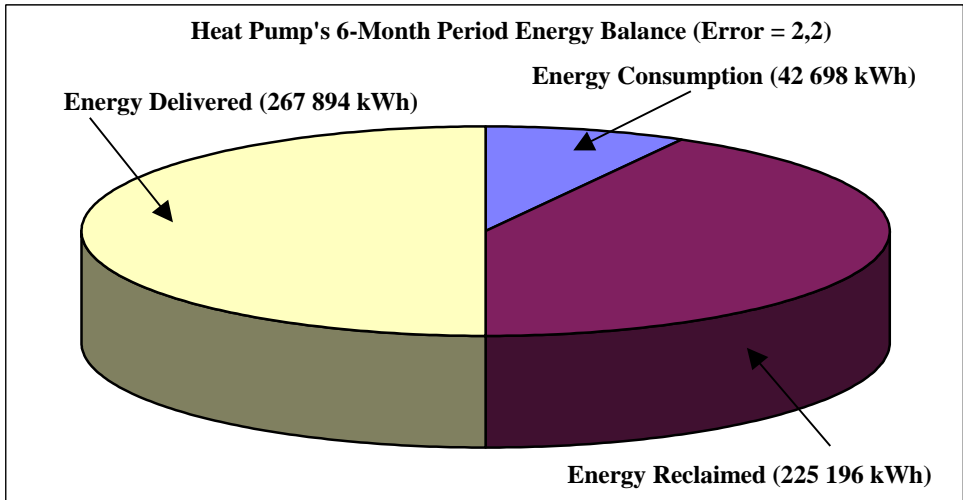


Figure 3.7 – Heat Pump’s Energy Balance During the 6-Month Production Period

The heat recovered by the heat pump corresponded to an average thermal power of approximately 52 kW, while the thermal energy provided by the heat pump to the groundwater represented an average seasonal thermal power of 60,4 kW. A relatively small energy balance error (2,2%) is due to the high precision of the instruments used and few transient operational regimes. The average passive heat exchanger thermal efficiency varied around 66%. As mentioned above, this lower-than-expected result can be linked to the periodic clogging of the heat exchanger. However, during and after using the chemical-based cleaning developed method, a substantial increase (up to 15%) in thermal efficiency was observed. The passive heat exchanger provided more than 472 000 kWh of thermal energy to the groundwater, corresponding to an average seasonal thermal power of 109 kW. By adding the average seasonal thermal power supplied by the heat recovery system, this figure becomes 169 kW. In terms of energy, the fresh groundwater was first heated by the passive heat exchanger, which provided 64% of the energy, and then by the heat pump, which provided 30,5% over six months of production (Figure 3.8). The heat pump energy reclaim and transfer were made possible by a net electrical consumption of 45,8%, while the water circulation pumps consumed 54,2% of the total energy supplied to the system. The average coefficient of performance calculated for the whole system including the passive heat exchanger and heat pump, was 7,9 for the two, 3-month periods of industrial production.

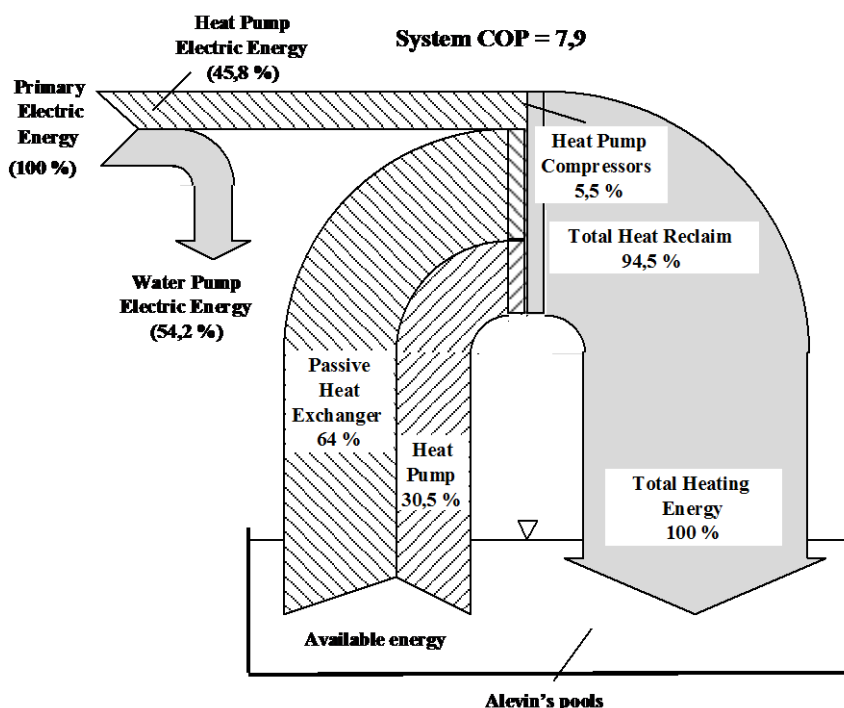


Figure 3.8 – Global Energy Balance of the Heat-Reclaim Water-Heating System

Using the local average price for electrical energy, the system's specific energy cost was about CAN\$4,20/(L/min)/°C, since the average raise in groundwater temperature was approximately 4°C. The operating cost savings of the heat recovery system were evaluated by comparing them with two conventional heating systems: "system A" having a passive heat exchanger and an electric heater, and "system B" with the same passive heat exchanger and an oil furnace. The simple pay-back period of the initial investment for the heat recovery system developed for this project, calculated as a ratio of the difference between construction costs and respective annual savings, is 1,3 years as compared to "system A", and one year as compared to "system B", without taking into account the savings due to increased fish production. In fact, a parallel study showed that heating the water of the incubation and nursery unit resulted in accelerated alevins growth (Champagne 1998). It was possible to compare the growth rate with heated (10 to 12°C) and unheated (7 to 8°C) fresh water. The annual production of 5-gram rainbow trout increased by approximately 50% by using water that was 4°C warmer. Moreover, the time period for rainbow trout growth was 65% shorter than with conventional processes, which led to substantial improvements in the company's overall efficiency. In fact, with the water temperature passing from 7 to 11°C, average alevin's weight after a 90-day period increased from the traditional 1,7 grams to 4,8 grams. Finally, assuming a fish sale price of CAN\$140/1000 units, the additional profits resulting from using the heat reclaim heating system developed for this project in the incubator and fish nursery, compared to a system without any heating device, were about CAN\$28 000/year. In addition, the fish showed an increased biological performance at feeding time.

#### 4. CONCLUSION

This study demonstrates that a heat pump heat recovery system accelerates alevin's growth, has a high seasonal coefficient of performance and reduces energy consumption and air pollution in comparison to a conventional oil-burning system. This heat reclaim heating system provides several advantages by facilitating the onset of feeding in salmonid sac fry and accelerating the production of larger alevins (5 grams and more), while increasing

productivity. The groundwater, with an initial temperature of approximately 7°C, was heated first in a passive heat exchanger and then in a heat pump with thermal energy recovered from the waste water. The average water temperature heated in this way varied between 10 and 11,9°C, so that the seasonal average increase was approximately 4°C. The seasonal average thermal power of the recovery system was approximately 169 kW, of which 109 kW came from the passive exchanger and 60 kW from the heat pump. The seasonal thermal efficiency of the passive heat exchanger was 66%, while the coefficient of seasonal performance of the heat pump was 6,1. For the entire heat recovery system, the coefficient of seasonal performance was 7,9. It was recommend to clean the passive exchanger on a weekly basis using chemical substances in appropriate concentrations, installing a desuperheater on the heat pump in order to preheat the rotary filter cleaning water and also, periodically, to clean the existing rotary filter with hot water. Considering the remarkable energy performance obtained, it was finally recommend to heat the water of most fish nurseries using the developed energy recovery method with passive heat exchanger and heat pump.

## ACKNOWLEDGMENTS

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