Energy Efficiency Test on Two Oyster Steam Tunnels

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ABSTRACT

TESTS were conducted from November 1981 to March 1982 on two oyster steam tunnels to determine the energy efficiency of the steam tunnel for opening oysters. As oysters were conveyed through an enclosed tunnel, steam was applied on the oysters to relax the adductor muscle, thus facilitating the opening of oysters by hand. Thermocouple probes inserted through the shells of sample oysters monitored the oyster meat temperature as the oysters were conveyed through the tunnel. This procedure was performed with single layer and multi-layer oysters on the conveyor belt to compare the effect of layering on energy efficiency. The energy efficiency was evaluated by determining: (a) time required for oyster meats to reach 49 °C; (b) heat penetration rate through the oyster, and (c) tunnel to oyster heat transfer efficiency.

The results showed that using a single layer of oysters a higher energy efficiency was obtained. However the efficiency was low in all cases. The results were used to propose specific design and operation guidelines which should enhance the future development of the oyster steam tunnel.

INTRODUCTION

As the oyster steam tunnel becomes more widely used in the oyster processing industry, it becomes increasingly important to establish design and operation guidelines that will maximize the productivity of the steam shucking process. Since oyster steaming is an energy intensive process requiring large amounts of steam energy, design and operation criteria which minimize energy consumption must be considered.

The objective of this research was to determine the energy eficiency of two oyster steam tunnels. This was accomplished by evaluating oyster meat and tunnel air temperatures as functions of the oyster travel time through the steam tunnel. Based on the results, several structural and operational modifications were proposed to improve the energy efficiency as well as the overall capability of the steam tunnel to open oysters.

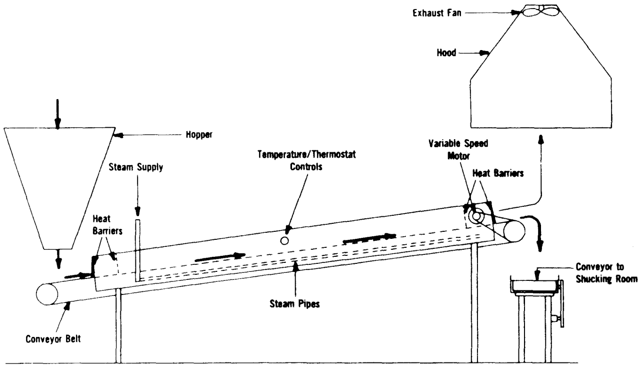

Fig. 1—Oyster steam tunnel.

STEAM TUNNEL PROCESS

The oyster steaming process facilitates the opening of oysters by hand. As live oysters are exposed to steam, their adductor muscles relax and the labor required to open the shells is thus reduced. Using this method oyster processors can realize a 20 to 35% increase in volume of meat produced (Tanchoco and Coale, 1980).

The oyster steam tunnel is a structure through which oysters are conveyed while being steamed (Fig. 1). When the oysters exit they are opened by hand and subsequently canned and marketed as a fresh product. As a general rule, oyster meat temperature should not exceed 49 °C if it is to be considered a fresh product (Huang, 1980).

TUNNEL DESCRIPTION AND OPERATION

Tunnel 1

Unwashed oysters dumped from a hopper located at the entrance were conveyed through the tunnel on a steel chain link belt driven by a variable speed motor. Under normal operation, a layer of oysters approximately 8 cm thick was maintained on the belt while steaming.

The tunnel was enclosed by a top and two sides. No bottom was used. The interior surfaces were plate steel, 0.60 cm thick and exterior surfaces were plywood, 1.27 cm thick. Tunnel dimensions were: length, 3.66 m; width, 0.91 m; depth, 0.32 m. No insulation was used.

In order to reduce steam loss through the end openings, two rubber steam barriers were located at each end of the tunnel. The force of the oysters striking the barriers caused them to swing open to allow passage of the oysters.

Steam was distributed by four steam pipes running the length of the tunnel from a manifold located near the tunnel entrance. Each 2.54 cm diameter steam pipe was perforated every 15.24 cm by 0.64 diameter steam

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injection holes. Since these pipes were located beneath the oysters, the injection holes were oriented upward so that steam was directed on the oysters on the conveyor belt. The tunnel air temperature was manually maintained at about 85 °C (±2 °C variation).

The tunnel was inclined 7.5 deg to achieve natural flow of steam through the tunnel. A hooded exhaust fan at the exit end vented steam from the building.

Tunnel 2

Unwashed oysters were hand shoveled approximately 8 cm deep on to a steel chain link belt operated by a variable speed motor.

The completely enclosed tunnel was constructed with stainless steel interior surfaces and plate steel exterior surfaces, 0.32 cm and 0.64 cm thick respectively. Tunnel dimensions were: length, 3.66 m; width, 0.66 m; depth, 0.35 m. One rubber heat barrier at each end was used to reduce steam losses as oysters entered and exited the tunnel. No insulation was used.

Steam entering the tunnel near the mid section was distributed by two 2.54 cm diameter steam pipes extending the length of the tunnel. Both steam pipes were perforated with 0.64 cm diameter steam injection holes. The tunnel air temperature was maintained at 85 °C by a self actuating temperature regulator (±1 °C variation). The regulator sensor was located at the midsection of the tunnel.

A 9 deg incline of the tunnel and a hooded exhaust fan allowed the flow and ventilation of steam through the tunnel and out the building.

PROCEDURE

Equipment

Oyster meat temperature and tunnel air temperature were measured by copper-constantan thermocouples and recorded on a Monitor Labs Model 9300 Data Log Computer*.

Oyster Preparation

Each test oyster was prepared by washing and hand drilling a 0.5 cm hole through the shell. A thermocouple was then inserted through the drilled hole and buried into the oyster meat. A loop of the thermocouple wire was fastened to the oyster shell with a rubber band to prevent dislodging of the thermocouple from the oyster. A heat resistant putty compound was placed around the drilled hole to prevent outside heat from entering the oyster at this point.

Temperature Tests

Experimental (single layer) and production (multi-layer) tests were conducted on each tunnel. In the experimental tests, only test oysters were conveyed through the tunnel. In production tests, test oysters were mixed in with a normal batch of production oysters. This procedure was followed so that the effect of the oyster layer thickness could be determined.

Each experimental and production test was conducted by equally spacing three oysters across the conveyor belt. In the production tests, the test oysters were also placed at random depths. The tunnel air temperature was recorded by fastening a thermocouple on the outside of an oyster's shell and conveying it with the three test oysters. As the oysters travelled through the tunnel, the thermocopule leads were hand fed into the tunnel. Five production and four experimental tests were conducted on tunnel 1 and four production and five experimental tests were conducted on tunnel 2. Temperatures were recorded every 15 s in tunnel 1 and every 5 s in tunnel 2.

TABLE 1. OYSTER AND TUNNEL TEMPERATURES FOR TUNNEL 1

Time, s	Tunnel, °C	Production oysters, °C	Experimental oysters, °C
0	19.9	18.6	21.3
15	51.2	19.8	21.7
30	57.9	21.8	23.6
45	71.9	24.8	26.9
60	74.5	27.9	30.7
75	74.5	30.6	34.2
90	76.9	33.2	37.9
105	80.9	36.1	41.4
120	83.9	38.9	45.2
135	87.2	41.9	48.8
150	91.6	43.8	52.4

Statistical Analysis

Average oyster meat temperatures for each test were determined by averaging the three meat temperatures at each time interval. Overall average temperatures were then calculated by averaging the average results of each test.

All tests were tested for linear and non-linear responses. A Statistical Analysis System (SAS) stepwise general linear modelling procedure (Ott, 1977) was used in testing several relationships that predicted tunnel air temperature and other meat temperature. The statistical significance of the relationships were determined by considering R^2 values, F-tests on the test variances, and t-tests on the estimated regression coefficients prior to normalizing initial temperatures. Statistical analyses

TABLE 2. OYSTER AND TUNNEL TEMPERATURES FOR TUNNEL 2

Time, s	Tunnel, °C	Production oysters, °C	Experimental oysters, °C
0	24.5	16.9	13.5
5	36.2	17.1	13.6
10	45.3	17.4	13.8
15	50.0	18.0	14.3
20	53.1	18.7	15.1
25	57.6	19.4	16.0
30	59.7	20.2	17.1
35	63.2	21.1	18.2
40	66.0	21.9	19.4
45	69.3	22.8	21.0
50	72.6	23.8	22.7
55	75.1	24.8	24.6
60	77.3	26.9	26.9
65	78.8	28.8	29.5
70	80.0	31.1	31.9
75	81.8	33.5	34.2
80	82.5	35.9	36.4
85	83.2	38.2	38.7
90	84.3	40.3	40.8
95	84.4	42.2	43.0
100	84.9	43.9	45.2
105	84.8	45.4	47.4
110	85.2	46.8	49.3
115	85.3	48.2	50.9
120	84.9	49.4	52.6
125	85.3	50.4	54.2
130	85.0	51.3	55.8
135	84.9	52.6	57.3

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*The use of trade names in this report does not imply endorsement of the product nor criticism of other products not mentioned.

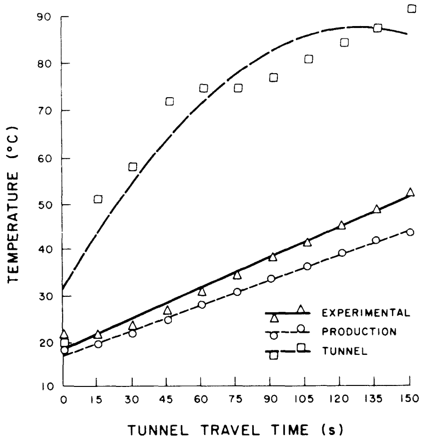

Fig. 2—Oyster meat temperatures and tunnel air temperature as a function of tunnel travel time (Tunnel 1).

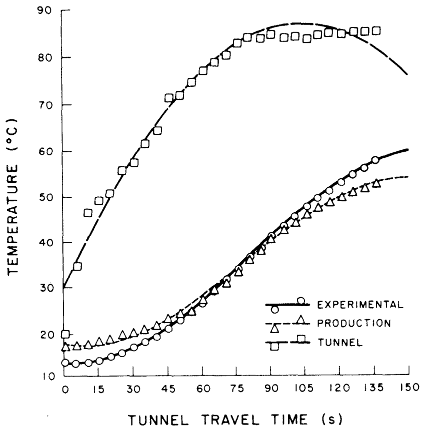

Fig. 3—Oyster meat temperature and tunnel air temperature as a function of tunnel travel time (Tunnel 2).

also included the computation of the mean values, standard deviation of the means, and standard errors of the estimated regression coefficients.

RESULTS AND DISCUSSION

Average oyster meat temperatures and tunnel air temperatures were recorded in Table 1 and Table 2 for tunnel 1 and tunnel 2 respectively.

Temperature Versus Time

Plots of oyster meat temperature and tunnel air temperature versus time were made (Figs. 2 and 3). Initial oyster meat temperatures varied by 7.8 °C between tunnel 1 and tunnel 2 depending on storeroom temperatures. Since an accurate evaluation and comparison of the heat transfer performance of the tunnels should reflect normalized starting temperatures of the oysters, an average initial temperature was used in the meat temperature regression equations. The average (16.87 °C) was determined by averaging all initial oyster meat temperatures as calculated from the actual regression equations. The regression equations were then vertically adjusted to account for the shift in the initial temperatures.

Expressed as functions of tunnel travel time (x = tunnel travel time, s) experimental meat temperature (EMT), production meat temperature (PMT), and tunnel air temperature (TAT) were define by equations [1] through [6].

Tunnel 1:

$$\text{EMT, } ^\circ\text{C} = 0.221x + 16.87 \quad \ldots\ldots\ldots\ldots [1]$$

$$\text{PMT, } ^\circ\text{C} = 0.178x + 16.87 \quad \ldots\ldots\ldots\ldots [2]$$

$$\text{TAT, } ^\circ\text{C} = 31.10 + 0.881x - 0.0034x^2 \quad \ldots\ldots\ldots\ldots [3]$$

Tunnel 2:

$$\text{EMT, } ^\circ\text{C} = 16.87 - 0.076x + 0.0066x^2 - 0.0000272x^3 \quad \ldots\ldots\ldots\ldots [4]$$

$$\text{PMT, } ^\circ\text{C} = 16.87 - 0.1307x + 0.0067x^2 - 0.0000278x^3 \quad \ldots\ldots\ldots\ldots [5]$$

$$\text{TAT, } ^\circ\text{C} = 32.47 + 1.03x - 0.0049x^2 \quad \ldots\ldots\ldots\ldots [6]$$

Analyses of variance on the relationships yielded R^2 values greater than 0.98. The F and t-tests on the regression variances and estimated coefficients were significant at the 0.0001 level.

Experimental Versus Production Meat Temperatures

Experimental meat temperatures were greater than production meat temperatures in tunnel 1 (Fig. 2). This was expected since surrounding oysters in the production tests prevented the higher heat transfer that was possible in the experimental tests.

In tunnel 2 the experimental meat temperatures was initially lower than the production meat temperature (Fig. 3). By comparing starting temperatures it was seen that the experimental oysters are approximately 3 °C colder than the production oysters, accounting for this inconsistency. Upon heating the oysters, the experimental temperature moved rapidly upward and finished higher than the production temperature.

Tunnel Travel Time

The steaming time required to bring oyster meat to 49 °C was determined by using the meat temperature regression equations. The results are shown in Table 3. The time required for production oysters to reach 49 °C was longer than the time required for experimental oysters. Thus the effect of oyster layers was apparent since multi-layer oysters required additional steaming time compared to single layer oysters.

Heat Penetration Rate

Oysters stacked several layers deep on the conveyor belt were expected to demonstrate lower heat penetration rates compared to oysters in a single layer. In order to

TABLE 3. HEATING TIMES, HEAT PENETRATION RATES, AND HEAT TRANSFER EFFICIENCIES OF TUNNELS 1 AND 2

Tunnel	Test	Heating time, min	Heat penetration rate, kJ/h	Heat transfer efficiency, %
1	experimental	2.42	170.33	30.41
	production	3.00	137.40	24.49
2	experimental	1.70	242.47	32.90
	production	1.95	211.38	26.34

observe this difference, average heat penetration rates were calculated for production and experimental tests.

Using the relationship proposed by Mashburn (1980) to calculate the energy needed to heat an oyster to 49 °C from a given initial temperature, it was determined that 6.87 kJ were required to heat an average oyster from 16.87 °C to 49 °C. This value was used to calculate the average heat penetration rates by dividing the time required to heat oysters to 49 °C into 6.87 kJ. The results are recorded in Table 3.

The production heat penetration rates were lower than the experimental heat penetration rates in both tunnels. This difference clearly demonstrated that the number of oyster layers on the conveyor belt effected the heat penetration rate through the oysters.

Heat Transfer Efficiency

In order to provide an indication of the heat transfer efficiency of the steam tunnels, an expression based on the ratio of the area under the oyster meat temperature curve to the area under the tunnel air temperature curve was used. This ratio represented the percentage of available measurable tunnel heat effectively penetrating the oyster shells and heating the oyster meats. The relationship was expressed as:

$$\text{H. T. Efficiency} = \frac{\int_a^b (\text{Oyster meat temperature})dx}{\int_a^b (\text{Tunnel air temperature})dx}$$

In this equation dx represented the incremental change in oyster travel time through the tunnel, and a and b referred to the beginning and ending of the oyster travel time. For tunnel 1 the travel time was 150 s and for tunnel 2 it was 135 s.

Since the oysters were already at an average temperature of 16.87 °C before entering the steam tunnels, steam had no effect on raising oyster temperatures to this point. Thus 16.87 °C was subtracted from the oyster meat and tunnel air temperature equations to compute the heat transfer efficiency (H. T.) of both tunnels. The results were recorded in Table 3 and were calculated as follows:

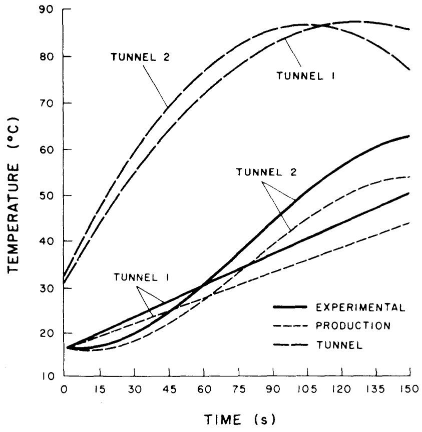

Fig. 4—Comparison of oyster meat and tunnel air temperatures of Tunnel 1 and Tunnel 2 at the same starting temperatures.

Comparison of Tunnels

In Fig. 4, equations [1] through [6] were superimposed to compare tunnels 1 and 2. Both experimental and production oyster meat temperatures in tunnel 1 followed a linear relationship, whereas in tunnel 2 these temperatures followed a non-linear relationship.

Comparing the oyster temperatures in each tunnel, oysters heated more rapdily in tunnel 2 compared to tunnel 1 and consequently required less steaming time. Also the heat penetration rate was significantly higher in tunnel 2. These higher values indicated that tunnel 2 had a greater capability to handle large volumes of oysters in a given time period or to steam a given quantity of oysters more rapidly compared to tunnel 1.

Locating the inlet steam manifold at the entrance of tunnel 1 may have caused the linear heating rate. The steam in this case was able to more uniformly heat the oysters as steam and oysters travelled through the tunnel.

In tunnel 2 the inlet steam manifold was located near the mid section and may have caused the non-linear heating rate. Also the steep inclination angle (9 deg) was considered excessive. These design features prevented steam from travelling downward to the entrance, thus causing an uneven steam distribution and heating rate in

Tunnel 1

$$\text{H. T. (experimental)} = \frac{100 \int_0^{150} (0.221x)dx}{\int_0^{150} (14.23 + 0.881\,x - 0.0034x^2)dx} = 30.41\%$$

$$\text{H. T. (production)} = \frac{100 \int_0^{150} (0.178x)dx}{\int_0^{150} (14.23 + 0.881x - 0.0034x^2)\,dx} = 24.49\%$$

Tunnel 2

$$\text{H. T. (experimental)} = \frac{\int_0^{135} (-0.076x + 0.0066x^2 - 0.0000272x^3)dx}{\int_0^{135} (15.6 + 1.03x - 0.0049x^2)dx} = 32.90\%$$

$$\text{H. T. (production)} = \frac{100 \int_0^{135} (-0.1307x + 0.0067x^2 - 0.0000278x^3)dx}{\int_0^{135} (15.6 + 1.03x - 0.0049x^2)dx} = 26.34\%$$

the tunnel. As a result approximately one third of tunnel 2 was under utilized.

The heat transfer efficiencies of both tunnels were similarly poor. Tunnel 2 however exhibited slightly higher values compared to tunnel 1. By locating the inlet steam manifold at the entrance and reducing the inclination angle of tunnel 2, the heat transfer efficiency of tunnel 2 would be expected to improve. Under these conditions oysters would be exposed to a given quantity of steam for a longer time period. This would also decrease the required tunnel travel time and increase the heat penetration rate through the oysters. Although the heat transfer efficiency of tunnel 1 was below the heat transfer efficiency of tunnel 2, the addition of a bottom was expected to significantly reduce steam loss and improve the performance of tunnel 1.

CONCLUSIONS

Since the steam tunnels tested in this research were representative of most oyster steam tunnels used in the oyster industry, the overall energy efficiency of the steam tunnel was considered below its maximum potential. The following design and operation considerations are suggested in order to increase the heat transfer between the tunnel and oysters.

1. Design considerations
   - (a) Locate the inlet steam manifold at or near the entrance of the tunnel.
   - (b) Steam oysters from bottom and top. Steam pipes running above and beneath the conveyor belt could be supplied with steam from two manifolds, one above and the other beneath the belt.
   - (c) Enclose and insulate the tunnel on all sides.
   - (d) Use flexible heat barriers at each end of the tunnel. If necessary, use several at each end to prevent excessive amounts of steam from escaping the tunnel.
   - (e) Incline tunnel to allow steam to move slowly to the exit end. Do not incine more than necessary. A 4 to 5 deg incline should be sufficient.
   - (f) Correctly size the exhaust fan. An oversized fan will draw steam from the tunnel and an undersized fan will not vent steam adequately.
   - (g) As an alternative to venting steam, use this waste steam to preheat oysters prior to steaming.

2. Operation considerations
   - (a) Wash oysters before steaming. Mud and debris on the oysters reduce the heat transfer between the tunnel and oysters.
   - (b) Maintain a minimum number of oyster layers on the conveyor belt.
   - (c) If oysters are consistently oversteamed, lower the tunnel air temperature rather than increase the conveyor belt speed. If oysters are consistently understeamed, decrease the conveyor belt speed rather than increase the tunnel air temperature.
   - (d) Periodically disconnect and check tunnel temperature gages. Replace if the condition or accuracy of the gage is questionable.

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