Frozen Storage of Skin, Parathyroid Gland, and Intestine

Techniques developed in this laboratory for storage of animal skin have been extended to a human skin bank.[3] Thin grafts of skin were treated with 10% glycerol, frozen at 1–10°C/min, stored in liquid nitrogen at −196°C for up to 19 months, and thawed rapidly for use by immersion in warm saline solution at 25–100°C/min. These grafts provided temporary lifesaving coverage for patients with extensive burn wounds before being rejected immunologically.

The same techniques have been extended successfully to the storage of canine parathyroid glands, tiny glands that control calcium metabolism. These frozen preserved glands can sustain the life of the animal.

Short segments of canine intestine treated in the same fashion have survived freezing in liquid nitrogen for as long as five weeks. The intestinal segments were distended to the shape of a thin walled hollow cylinder. Warm saline solution was introduced on both sides of the intestinal wall for rapid thawing by conduction. The segments required one to two weeks of cellular recovery from freezing injury to resume normal function which included muscular action, secretion of mucus, and absorption of glucose. This success indicated that the several cell types of a single organ would survive a common cryoprotective treatment.[4] Determination of optimal concentrations of cryoprotective agents and satisfactory control of organ edema are problems still to be solved.

Frozen Storage of Solid Organs

Special problems exist in the frozen storage of large solid organs such as kidney, heart, and liver.[5] Heat exchange in the living animal is rapid because of the intimate contact of the circulatory system with all of the cells. Internal temperature gradients are small. In contrast, large thermal gradients develop during heat exchanges in frozen solid organs. These resemble blocks of frozen salt solutions in their thermal properties of low-heat conductivity, high-heat capacity, and large heat of fusion. The low ratio of surface area to volume for solid organs severely limits heat exchange with the surroundings (see Table 2). Satisfactory rates of thaw cannot be achieved by immersion in warm liquids. Perfusion of the blood vessels with gases is a potential means of internal heating, limited by the low rate of heat transfer from the gas to the organ.

Electrical Thawing

Electrical heating, by generating heat within the substance of solid organs, can overcome the problem of poor thermal conductivity. Uniform heating is dependent on the distribution of the electrical field and the local electrical resistance of the tissue. The electrical properties of tissues are similar to those of dilute aqueous salt solutions. The electrical conductivity is a function of temperature over a wide range of frequencies. There is a rapid rise in conductivity increasing with rising temperature when tissue passes from the frozen to the thawed state. Recently, canine kidneys were thawed at 50–100°C/min using a microwave oven operating at 2450 MHz.[6] Although a satisfactory over-all thawing rate of 60–100°C/min was attained, none of the eight kidneys survived after reimplantation. On closer inspection it was obvious that heating was far from uniform. Certain areas of some kidneys overheated, even to the point of burning, while adjacent areas remained cold or frozen.

That microwave thawing is not inherently toxic to cells was established by a comparison of frozen skin grafts thawed by microwave and by thermal conduction techniques. Skin grafts survived after microwave thawing although there was some damage associated with focal overheating.

This phenomenon of uneven thawing during electrical thawing, named thermal runaway, was investigated using a two-dimensional mathematical model and a digital computer.[7] Isotherms were calculated over the period of time required for thawing of the model. The experimentally observed increase in electrical conductivity with increasing temperature was included in the equation of the model. The analysis verified the nonuniform characteristics of the thaw with some areas remaining frozen while others overheated. Important variables were the temperature at the beginning of the electrical thaw, the temperature at the boundary of the organ, and the strength of the applied electrical field during the thaw. Experiments performed using electrical conduction thawing at low frequency verified the conclusions of the mathematical model study.[8]

Conclusions

The need for a human organ bank for transplantation is great. The extrapolation of techniques proven successful in the frozen storage of cells has proved extraordinarily difficult for large solid organs. The constraints imposed by the properties of biological tissue render the control of heat exchange very difficult. It is hoped that proper application of engineering principles within these specific limitations of biological tissues will permit satisfactory rates of heat exchange. Further refinement of cryoprotective perfusion techniques are needed. Better methods of suppressing edema are urgently needed. The fact that certain organs have survived freezing makes the creation of a frozen organ bank for transplantation a likely event.

References

[1] Belzer, F. O. et al., "Isolation Perfusion of Whole Organs," *Organ Perfusion and Preservation*, Appleton Century Crafts, New York, 1968, pp. 3–12.

[2] Meryman, H. T., *Cryobiology*, Academic Press, New York, 1966, pp. 1–775.

[3] Berggren, R. B. and Lehr, H. B., "Clinical Use of Viable Frozen Human Skin," *Journal of the American Medical Association*, Vol. 194, No. 2, Oct. 1965, pp. 149–151.

[4] Hamilton, R. and Lehr, H. B., "Survival of Small Intestine After Storage for Seven Days at −196°C" *Cryobiology*, Vol. 3, No. 5, March-April 1967, p. 375.

[5] Hamilton, R. et al., "Frozen Organ Banks: Progress and Problems," *Current Topics in Surgical Research*, Vol. 1, Academic Press, New York, 1969, pp. 17–27.

[6] Hamilton, R., Ketterer, F. D., and Hoist, H. I., "Rapid Thawing of Frozen Canine Kidneys by Microwaves," *Cryobiology*, Vol. 4, No. 5, March-April 1968, pp. 265–266.

[7] Allen, J. and Ketterer, F. D., "Analytical Investigation of Thermal Runaway During Electrical Thawing of Frozen Tissue," *Cryobiology*, Vol. 4, No. 5, March-April 1968, p. 248.

[8] Kenney, J. and Ketterer, F. D., "Kidney Thawing by Conduction Heating," *Cryobiology*, Vol. 4, No. 5, March-April, 1968, p. 248.

Calculation of Maximum Velocity Decay in Wall Jets

P. Hrycak* and D. T. Lee†
Newark College of Engineering, Newark, N.J.

Nomenclature

b = outer boundary-layer thickness
C = constant
D = nozzle diameter
K = δ/b

Received December 24, 1969; revision received February 2, 1970. This work has been partially supported by NASA under NGR-31-009-004.

* Professor of Mechanical Engineering. Member AIAA.
† Graduate Assistant, Mechanical Engineering Department; Present Addresss: Georgia Institute of Technology, Atlanta, Ga.

n = parameter in turbulent velocity profile
r = coordinate parallel to the wall
r_0 = virtual origin location
Re_D = jet nozzle Reynolds number, U_0D/ν
U_0 = original jet nozzle velocity
V = velocity in the r direction
z = coordinate perpendicular to the wall
$z_{1/2}$ = jet width where $V = \frac{1}{2}V_m$ in the outer layer
z_n/D = dimensionless vertical distance between wall and nozzle
δ = inner boundary layer thickness
ξ,θ = $(z - \delta)/b$ and z/δ, respectively
ν = kinematic viscosity

Introduction

As opposed to free jets, where the momentum is conserved and where simple rules concerning maximum velocity decay have been established,[1] wall jets are strongly influenced by wall friction. A wall jet is obtained when, for example, a jet of air strikes a surface at the right angle and then spreads out as shown in Fig. 1. Because of the effects of friction at the walls, the maximum velocity decay for wall jets may be expected to be faster than in the corresponding free jet cases. For turbulent wall jets, there is at present still no entirely satisfactory analytical solution to the problem at hand. Therefore, integral methods will be tried below.

Maximum Velocity Decay, Turbulent Jets

The present analysis concerns itself with the region III of Fig. 1, where the flow reached already a modicum of similarity and where the effects of the pressure gradients are negligible. The velocities in question are low enough so that flow is incompressible.

The approach used by Abramovich[2] for various calculations involving two-dimensional wall jets may be generalized to get a relation involving the region of flow where the momentum is conserved, in analogy to the free jetflow. Starting with the control volume ABCD (Fig. 1), the momentum balance for the steady state, after differentiation with respect to r, results in the relation

$$V_m \frac{d}{dr}\int_0^\delta r^i V dz + \frac{d}{dr}\int_\delta^{b+\delta} r^i V^2 dz = 0 \tag{1}$$

where, for a two-dimensional wall jet, $i = 0$, and for a radial wall jet, $i = 1$. Now, letting the velocity of the inner layer be represented by $V = V_m\theta^{1/n}$, $0 < \theta < 1$, and the velocity of the outer layer by $V = V_m(1 - \xi^{3/2})^2$, $0 < \xi < 1$, with the dimensionless parameters, $\bar{r} = r/D$, $\bar{V} = V/U_0$, $\theta = z/\delta$, $\xi = (z - \delta)/b$, $\bar{\delta} = \delta/D$ and $\bar{b} = b/D$, and using also the result,

$$\int_0^1 V^2(\xi)d\xi = 0.3156V_m{}^2$$

one obtains

$$[n/(n+1)]\bar{V}_m(d/dr)(\bar{\delta}\bar{r}^i\bar{V}_m) + 0.3156(d/dr)(\bar{b}\bar{r}^i\bar{V}_m{}^2) = 0$$

Since the relations $b = C(r - r_0)^\beta$ and $\delta = Kb(0 < K < 1)$, with C and K being constants, are suggested from experimental observation,[2] this equation, after differentiation and simplification, yields

$$\left(\frac{Kn}{n+1} + 0.3156\right)\left(\frac{d\bar{b}}{\bar{b}} + \frac{d\bar{r}^i}{\bar{r}^i}\right) + \left(\frac{Kn}{n+1} + 0.6312\right)\frac{d\bar{V}_m}{\bar{V}_m} = 0 \tag{2}$$

Letting

$$[Kn/(n+1) + 0.3156]/[Kn/(n+1) + 0.6312] = \gamma$$

this equation integrates into

$$\bar{V}_m = A/[\bar{r}^{(i+\beta)\gamma}(1 - r_0/r)^{\beta\gamma}] \tag{3}$$

so that, for $r_0 \ll r$, and $(i + \beta)\gamma = \alpha$, the result is

$$\bar{V}_m = A/\bar{r}^\alpha \tag{4}$$

Comparison with Experimental Results

For two-dimensional wall jets, the experimental results described by Abramovich,[2] who also used $n = 7$, suggest $\beta = 1$ and $K = 0.1$, whereas from Schwarz and Cosart's data[3] one finds explicitly $n = 14$, while $K = 0.1$ can be deduced. This gives in Eq. (4) $\alpha = 0.560$, as compared to $\alpha = 0.555$ found in Ref. (3) experimentally. When $K \to 0$ (free two-dimensional jet), $\gamma = \alpha$ and $\alpha = \frac{1}{2}$, as may also be expected from dimensional considerations.[1]

For a radial wall jet ($i = 1$) shown in Fig. 1, formed by letting a free jet of air at ambient temperature impinge against a smooth flat plate from various vertical distance, z_n/D, the authors found[4] for developed turbulent jets $K = \frac{1}{9}$, $7.5 < n < 14$, and $\beta = 0.95$ (Fig. 2). The range of values of n

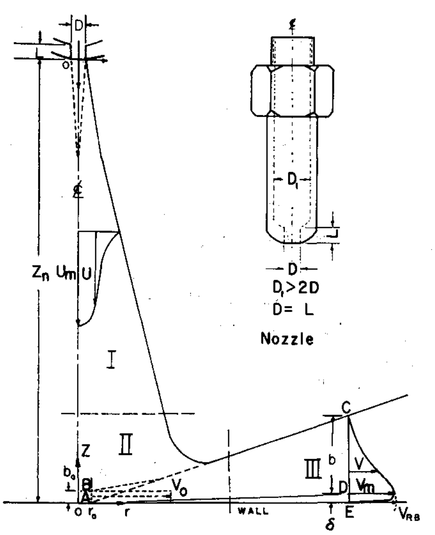

Fig. 1 Geometry of a wall jet: region I, freejet: region II, developing wall jet: region III, developed wall jet.

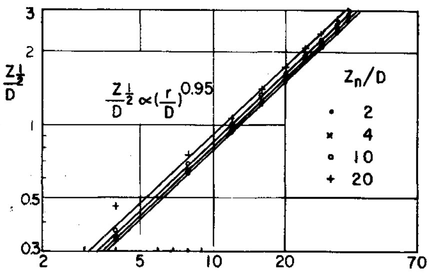

Fig. 2 Variation of half-velocity spread of a radial wall jet with distance from origin.

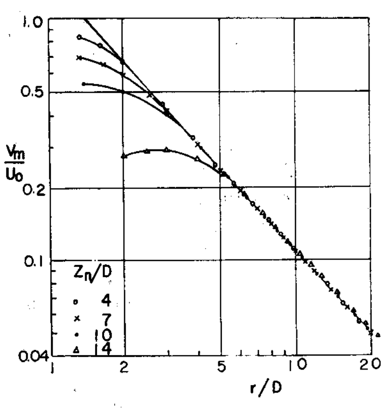

Fig. 3 Maximum velocity decay of a radial wall jet.

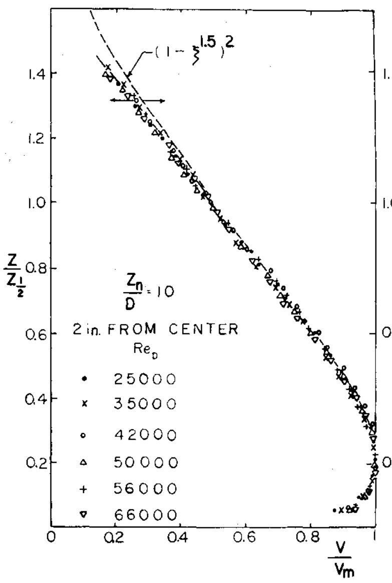

Fig. 4 Experimental velocity profile of a radial wall jet.

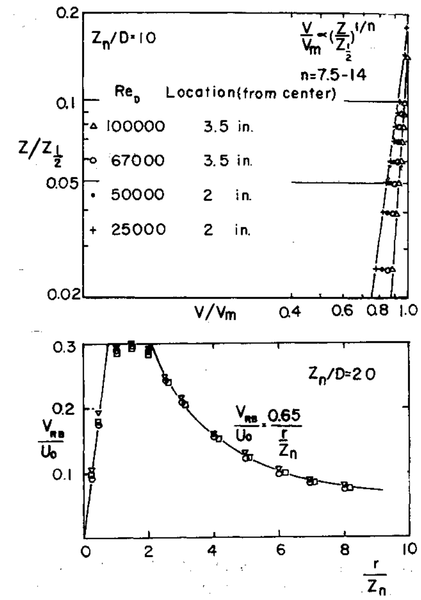

Fig. 5 Determination of n; V_{RB}/U_0 variation with r/z_n.

found corresponded to $n = 7.5$ for the jet nozzle Reynolds number (which is related to V_m) $Re_D = 2.5 \times 10^4$, and $n = 14$ for $Re_D = 10^5$, taken 2 in. and 3.5 in. from the center of symmetry, respectively.

The experiments were carried out with the nozzles (Fig. 1) having $D = \frac{3}{8}$, $\frac{1}{4}$, and $\frac{1}{8}$ in., respectively. Among the instruments used were a $\frac{1}{64}$ in. diam total pressure probe and a $\frac{1}{32}$-in.-diam static pressure probe of conventional design, which could be positioned within 0.01 in., and a micromanometer accurate within 0.001 in.

These experiments give α in Eq. (4) ranging from 1.11 to 1.12, which compares well with the experimental results in Fig. 3, where $\alpha = 1.12$. These values of α and β also compare well with those obtained experimentally by Bakke,[5] who formed a radial wall jet differently, by means of an annular orifice formed between a long flanged tube and a smooth flat plate ($\alpha = 1.12$, $\beta = 0.94$). Both experimental values of β were found indirectly, through the half-velocity spread parameter $z_{1/2}$, which for similar flow must be proportional to b.

For a free radial jet, again equivalent to $K \to 0$, $V_m \to V_{RB}$, and $\gamma \to \frac{1}{2}$, it may be deduced from conservation of mass that $\alpha = 1$, which also makes $\beta = 1$.

The velocity profiles used here are also experimentally verified (Fig. 4). The inner profile is similar to the corresponding turbulent velocity profile on the flat plate, only with a steeper slope with $n > 7$. The velocity profile in the outer layer has been found useful by Abramovich[2] and seems to fit the present data well. By plotting data for the inner layer on log-log paper, the values of n could be ascertained and $\alpha = 1$ is obtained from plotting V_{RB} against r/z_n (Fig. 5).

The absence of shear stress at $y = \delta$ in Eq. (1) is in agreement with Prandtl's hypotheses where the turbulent shearing stress is proportional to the derivative of velocity with respect to the coordinate normal to the flow direction,[1] $\partial V/\partial z$. Newer measurements[3] indicate that this is not quite so with the wall jets, but apparently this omission was not the overriding factor in the present case.

This discussion shows that the parameters α, β, K, and n in a wall jet are intimately interrelated. Knowing some three of these parameters allows to calculate the remaining one with a good degree of accuracy when integral methods are used, provided velocity profiles chosen correspond reasonably well to reality.

In general, the deviation of α from unity is the measure of wall friction: α increases slowly with n, which, in turn, is a function of the Re_D.[1] The authors also observed experimentally that substitution of a rough plate for a smooth one had a similar effect on α, as did steam heating of the plate, causing a slight increase of α. A comparison of turbulent wall jet flow with the turbulent flow over a flat plate shows that the velocity profile may be approximated by $\theta^{1/n}$, only n increases for wall jets faster with Re_D.

Maximum Velocity Decay, Laminar Jets

It is interesting to realize that the methods discussed in this Note can also be applied to laminar wall jets, where Eq. (1) holds exactly. Using now for the inner layer the relation $V = 2V_m(\theta - \frac{1}{2}\theta^2)$, and leaving the expression for the velocity distribution in the outer layer unchanged,

$$\gamma = (2K/3 + 0.3156)/(2K/3 + 0.6312)$$

is obtained.

Since the problem of the laminar wall jets has been fully solved by Glauert,[6] we can get from his solution $K = 1/2.2$, which makes $\gamma = 0.663$. This, for the radial wall jet ($\beta = 1.25$), leads to $\alpha = 1.49$, very close to the corresponding Glauert's result, as is also $\alpha = 0.497$, for the plane laminar wall jet, where $\beta = 0.75$.

Because Glauert's solution appears not in the explicit form, it is of some comfort to know that integral expressions are available which closely approximate the essential features of the exact solution.

References

1 Schlichting, H., "*Boundary-Layer Theory*," 6th ed., McGraw-Hill, New York, 1968, pp. 563, 681–702.

2 Abramovich, G. N., *The Theory of Turbulent Jets*, Massachusetts Institute of Technology Press, Cambridge, Mass., 1963, pp. 478–489.

3 Schwarz, W. H. and Cosart, W. P., "The Two-Dimensional Turbulent Wall Jet," *Journal of Fluid Mechanics*, Vol. 10, Pt. 4, June 1961, pp. 481–495.

4 Lee, D. T., "Experimental Investigation of Submerged, Incompressible, Turbulent, Impinging Jets," M.S. thesis, 1969, Newark College of Engineering, Newark, N. J.

5 Bakke, P., "An Experimental Investigation of a Wall Jet," *Journal of Fluid Mechanics*, Vol. 2, Pt. 5, July 1957, pp. 467–472.

6 Glauert, M. B., "The Wall Jet," *Journal of Fluid Mechanics*, Vol. 1, Pt. 6, Dec. 1956, pp. 625–643.