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AN ELECTROCHEMILUMINESCENT HEAT TRANSFER ANALOGY

by

WILLIAM A. SMILEY III

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Approved By:

Herbert Lew Ball

Major Professor

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NOMENCLATURE

Symbol	Significance	Units
b	adjustable constant in Equation [5]	Dimensionless
c	specific heat	BTU/lbm F
E	electric potential	Volt
g	acceleration of gravity	Ft/sec^2
$\bar{h}$	average unit-surface conductance	$BTU/hr\ ft^2\ F$
h_{cx}	local unit-surface conductance	$BTU/hr\ ft^2\ F$
I	electric current	Amperes
K	thermal conductivity	BTU/hr ft F
1	length	Ft.
q	rate of heat flow	BTU/hr
T_s	surface temperature	F
T_∞	bulk temperature of fluid	F
X	distance from leading edge of plate	Ft.

Greek

β	temperature coefficient of volume expansion	1/F
ρ	mass density	lbm/ft^3
μ	viscosity	lbm/ft hr

Dimensionless Groups

Gr	Grashof number	$\dfrac{\beta g \, l^3 \, (T_s - T_\infty)\rho^2}{\mu^2}$
Gr_x	local Grashof number	$\dfrac{\beta g \rho^2 X^3 (T_s - T_\infty)}{\mu^2}$
Pr	Prandtl number	$\dfrac{c\mu}{K}$
Nu	Nusselt number	$\dfrac{\overline{h}l}{K}$

Miscellaneous

a < b	a is less than b
a > b	a is greater than b
α	proportional sign

INTRODUCTION

In all convective heat transfer applications one must have a knowledge of the mechanisms by which heat is transfered between the surface of a solid conductor and the surrounding medium. The rate of heat transfered by convection is basically evaluated by means of equation [1].

$$q = A\overline{h} (T_s - T_\infty) \qquad\qquad [1]*$$

The convection equation in this form seems quite simple. The simplicity is misleading, however, because equation [1] is a definition of the average unit thermal convective coefficient, $\overline{h}$, rather than a law of convective heat transfer. The convective film heat transfer coefficient is actually a complicated function of the fluid flow, the thermal properties of the fluid medium, and the geometry of the system. Its numerical value is generally not uniform over the surface.

Although equation [1] is generally used to determine the rate of convective heat flow it is inadequate to explain the convective heat flow mechanism. A meaningful analysis of this mechanism must start with a study of the dynamics of fluid flow. For this reason much work has been done in the field of flow visualization. The symposium volume entitled Flow Visualization (1) gives a comprensive study of the various techniques used in flow visualization.

It was noted by Schraub (2) that most of these methods require the introduction of foreign objects into the flow which may disturb the actual

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* All symbols are defined in the nomenclature.

flow patterns, and cause error in interpreting results. A method of flow visualization with virtually no disturbance to the actual flow was originally presented by Howland, Pitts and Gesteland (3) in 1962. This method is known as an electrochemiluminescent (ECL) process.

An ECL process is defined as one in which two electrodes are submerged in a flow field of chemiluminescent solution and a voltage is applied between them and a reaction occurs at the anode emitting a blue glow.

All previous work done with ECL dealt with a forced flow field with no heat transfer taking place, and was used to study the flow patterns, while from the measured light intensity, mass transfer rates were evaluated. No previous work delt with heat transfer, natural convection or the current through the ECL process.

It was thought that if mass transfer rates could be measured, then, by the analogy between heat and mass transfer, heat transfer rates could also be predicted from the ECL results.

In the present study a method for the analysis of over-all and local convective heat transfer rates using an ECL process is discussed. A vertical flat plate was used as a test section because of the availability of references to compare results obtained. For the same reason all data was recorded in laminar flow only, with one exception. Two test runs were made into the turbulent region to determine if the method used could distinguish between laminar and turbulent free convective heat transfer. Instead of measuring the light intensity of the glow at the anode, the current through the ECL solution was recorded. It was thought that measuring the current might give a more exact representation of what was happening than measuring the light intensity. In addition, measuring the current was easier.

This method would give future investigators the possibility to simultaneously visualize the flow occuring in a convective heat transfer medium, both free and forced, and to evaluate the local convective heat transfer rates.

OBJECTIVE

An investigation was made into the possibility of obtaining a quanitative relationship between natural convective heat transfer rates and the reaction rate at the anode in an ECL solution by measuring the current through the ECL solution.

REVIEW OF LITERATURE

The first report of the ECL phenomenon was that of Harvey (4) in 1940. He discovered that when two electrodes were immersed in the flow field of a chemiluminescent solution and a voltage was applied between them, a blue glow appeared at the surface of the anode. All of the work published since then dealing with ECL has been done in a forced flow field, and deals with flow visualization and evaluation by measuring the light intensity of the blue glow.

Howland, Pitts and Gesteland (3) showed that, in a ECL flow field, the glow is generated within a few wavelengths of the anode, i.e. at a distance which is smaller than the thickness of the hydrodynamic boundary layer. Thus the technique of ECL is useful for studying those phenomena that occur at the wall. Also, since the glow covered the entire surface of the anode, the technique may be used to study both local and gross effects.

Springer (5) demonstrated that in laminar flow, for a given ECL solution and applied anode to ECL solution potential, the light intensity of the glow is directly proportional to the mass transfer, and by analogy to heat transfer, of the active electrolyte to the surface of the anode.

Schiller (6) and Howland, Springer and Hill (7) found that the ECL process can be used to visually determine the points of separation and the positions at which transition from laminar to turbulent flow occurs.

EXPERIMENTAL PROGRAM

The following section describes the test equipment used, the test section itself and the procedure followed when taking data.

Test Plate

The first material used for construction of the test plate was plexiglass. This didn't prove very satisfactory because the plexiglass could only stand an inside surface temperature of 220 F before distortion and, because of its high thermal resistance, this temperature gave a maximum outer surface temperature of 90 F and a 20 F difference, ΔT, between the outer surface and the bulk ECL solution temperature for the conditions at which the experiment was run. This did not give as high a ΔT as was desired. The method used for attaching a platinum strip (the anode) to the plexiglass also proved to be unsatisfactory. First the plexiglass was grooved to a depth and width comparable to the 24 gauge platinum wire used. Then scraps of plexiglass were mixed with plexiglass solvent to make an adhesive compatable to the plexiglass. The wire was then glued into the groove. After the glue had set up, the surface of the plexiglass was sanded smooth so that a thin strip of platinum was exposed. This method gave an overall smooth surface which was desirable but after only a few test runs in the solution the platinum wire came loose. Apparently the solution attacks plexiglass. For these reasons this test plate fabrication was discontinued.

A picture of the actual test plate is shown in Plate 1 and a detailed sketch in Figure 1. The test plate had outside dimensions of 3" x 1 1/2" x 3/8". It consisted of an inner mica sheet with a chromel A strip wound around it for the heater core. This heater core was sandwiched between two more mica sheets, and this assembly was then sandwiched between two brass plates. In order to prevent the entry of the ECL solution into the heater core, the brass plates were joined around the edges with solder and two brass tubes were attached to the top edge to provide a means of getting the leads from the heater core out of the test plate. The test plate was filled with Dow Corning 710 silicone fluid to provide better heat transfer from the heater core to the brass plates by replacing all the air spaces with a fluid that had better heat transfer properties. This also reduced the possibility of having hot spots on the test plate surface.

In order to insulate the platinum strip attached to the test plate, the brass plates were covered with Scotch type Y9242 tape. The platinum strip was attached to the tape in the following manner: first the two surfaces to be joined were cleaned with methyl alcohol. Next they were sanded with 400 grit sandpaper and cleaned again with Bean metal conditioner (an acidic solution). The conditioner was then neutralized with Bean neutralizer. The surfaces were now ready to be joined. For the joining process Eastman 910 adhesive was spread on the plate and Eastman 910 fixer on the strip. The strip was then pressed to the plate. Thus the platinum strip was attached to the tape covering the test plate.

A 36 gauge thermocouple was attached to the back side of the test plate in the same manner as was the platinum strip, as shown in Figure 1.
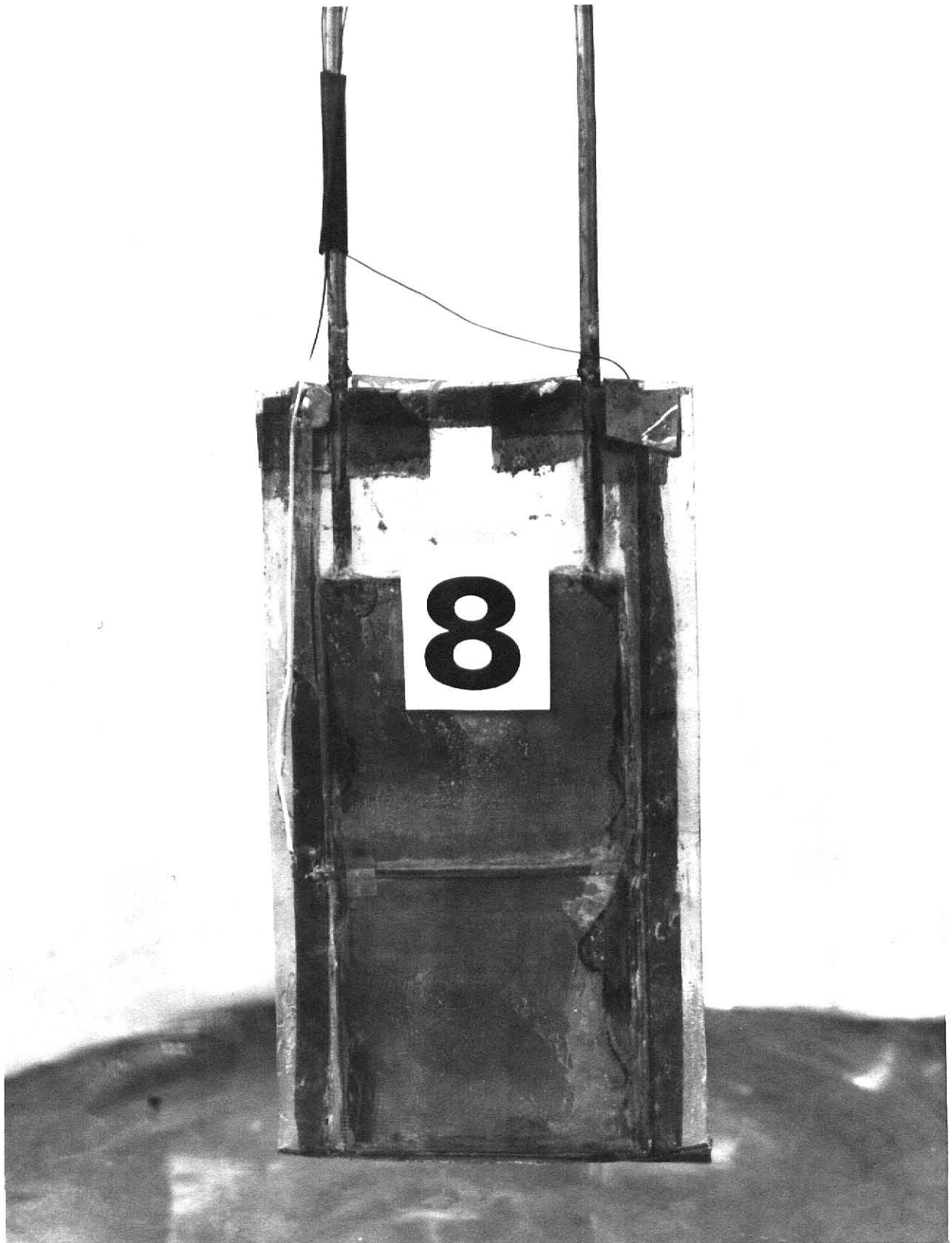
A thin strip of Scotch type Y9242 Tape was then put over the thermocouple. It was thought that this method of thermocouple attachment did not

PLATE I

Actual Test Plate

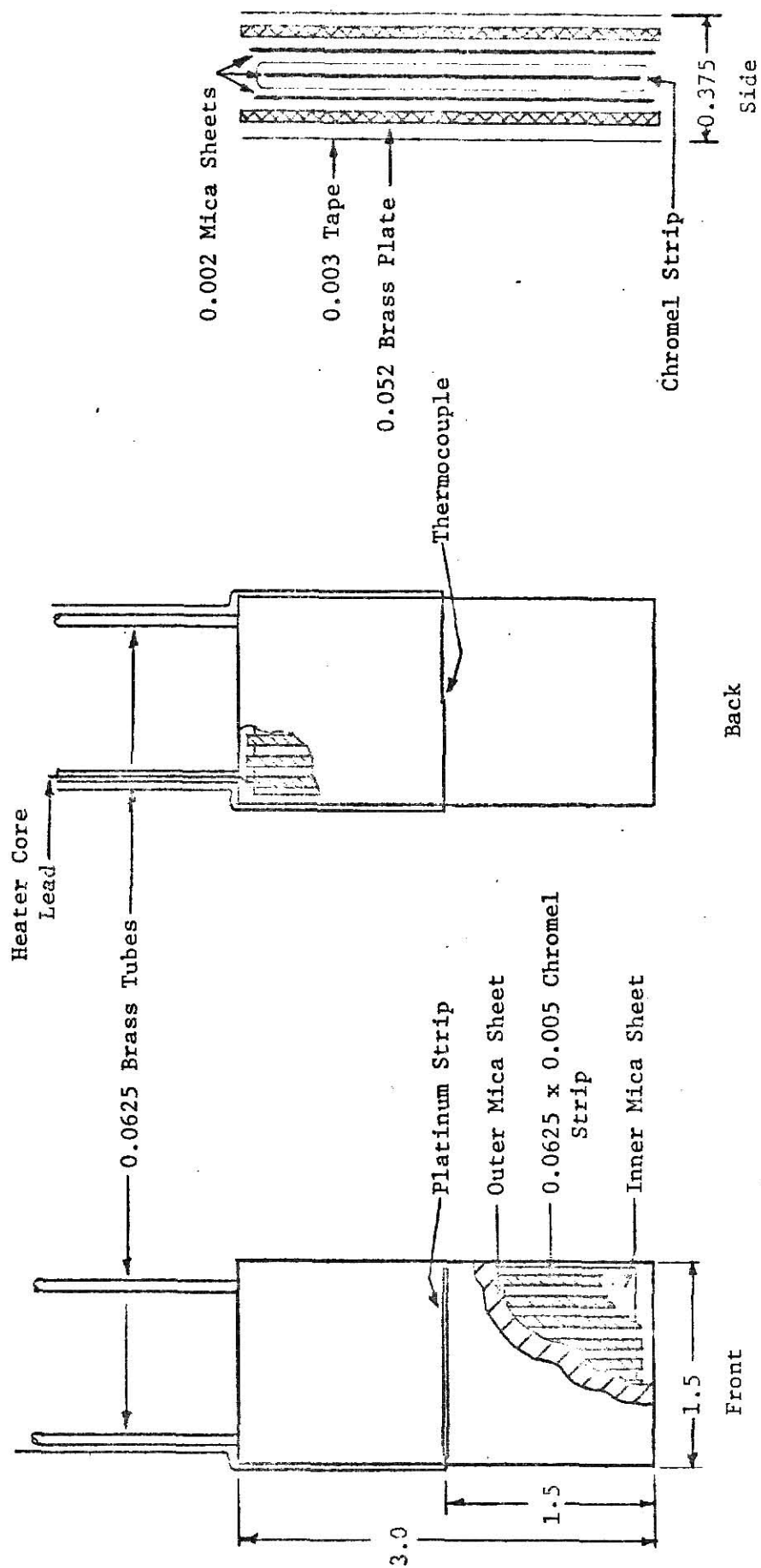PLATE I   8

Figure 1. Test Plate Assembly

give the true value of plate surface temperature. The thermocouple had only a point attachment to the plate. For that reason the thin strip of tape was put over it to trap a small amount of ECL solution so the thermocouple would be surrounded with a medium that was closer to the plate temperature than the bulk ECL solution. The error in plate temperature readings was not thought to be significant in this study.

The last test plate described was the one used in this study and while it held up for all the test runs considered in this study, the platinum strip came loose when enough energy was applied to the heater core to cause boiling at the surface of the test plate.

Test Apparatus

The apparatus used for this experiment consisted of three major groups: the heater group, the temperature measurement group and the current measurement group. A picture of the apparatus is shown in Plate 2.

2. Voltmeter
3. Ammeter
6. D.C. Power Supply
8. Test Plate
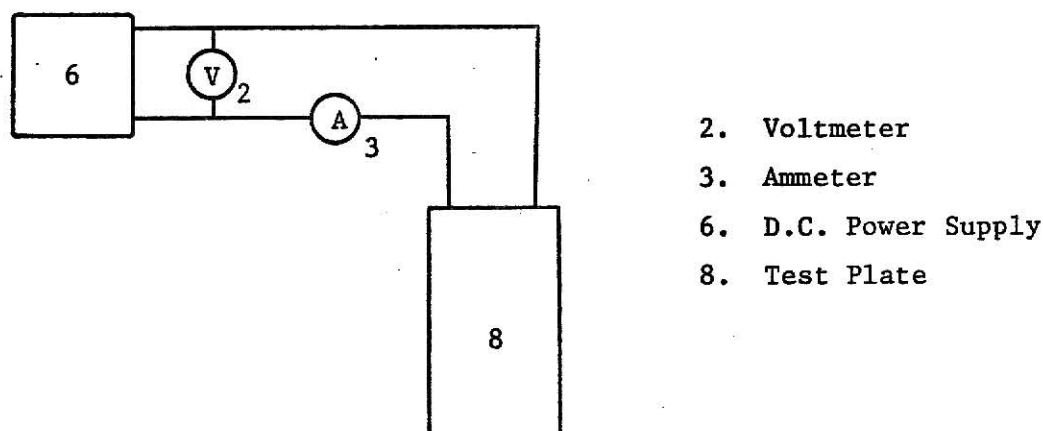
Figure 2. Heater Input Group

EXPLANATION OF PLATE II

Experimental Test Apparatus

ITEM	Description
1.	Millivolt Potentiometer
2.	Voltmeter
3.	Ammeter
4.	Channel Selector
5.	Ice Bath
6.	D.C. Power Supply
7.	4-Liter Beaker
8.	Test Plate
9.	Cathode
10.	Bulk ECL Solution Thermocouple
11.	D.C. Power Supply
12.	Ammeter
13.	Voltmeter

PLATE II 12

The heater group is schematically detailed in Figure 2. All schematic details are labeled according to Plate 2. Power to the heater core of test plate, 8, was supplied by a D.C. power supply, 6. The voltmeter, 2, and ammeter, 3, were used to measure the quantity of heater input to the test plate, both with a manufacturer's certified accuracy of ± 0.5% of full scale.

Figure 3 shows a schematic detail of the temperature measurement group. The output of the thermocouples was measured with the null balance millivolt potentiometer, 1, which could be read to the nearest 0.001 mv.

1. Millivolt Potentiometer
4. Channel Selector
5. Ice Bath Reference Junction
7. 4-Liter Beaker
8. Test Plate
10. Bulk ECL Solution
    Thermocouple
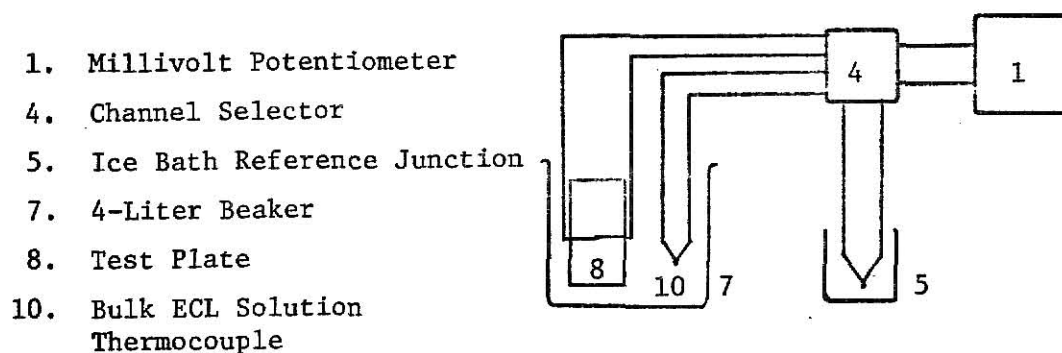
Figure 3. Temperature Measurement Group

The measured potential was then converted to degrees Fahrenheit from tables. The thermocouple system used an ice bath reference junction, 5, filled with distilled water and ice mixture. There were two temperatures measured, the surface temperature of the test plate, 8, and the bulk ECL solution temperature, 10. Both the bulk ECL solution and the test plate thermocouples were connected to a channel selector, 4, as was the ice bath

reference junction, so each thermocouple could be selected for reading by simple turning a selector switch to the appropriate channel.

The third major part of the apparatus was the current measurement group, shown in Figure 4. A D.C. power supply, 11, was used to apply a potential through the ECL solution contained in the beaker, 7, in which the test plate, 8, was placed. The voltage and current were measured with a voltmeter, 13, and an ammeter, 12, with manufacturer's specified accuracy of ± 0.5% of full scale and ± 3% of reading, respectively. The cathode, 9, was constructed of two one inch pieces of 24 gauge platinum wire and the anode was a one inch strip of one mil platinum foil, one millimeter wide attached to the test plate, 8.
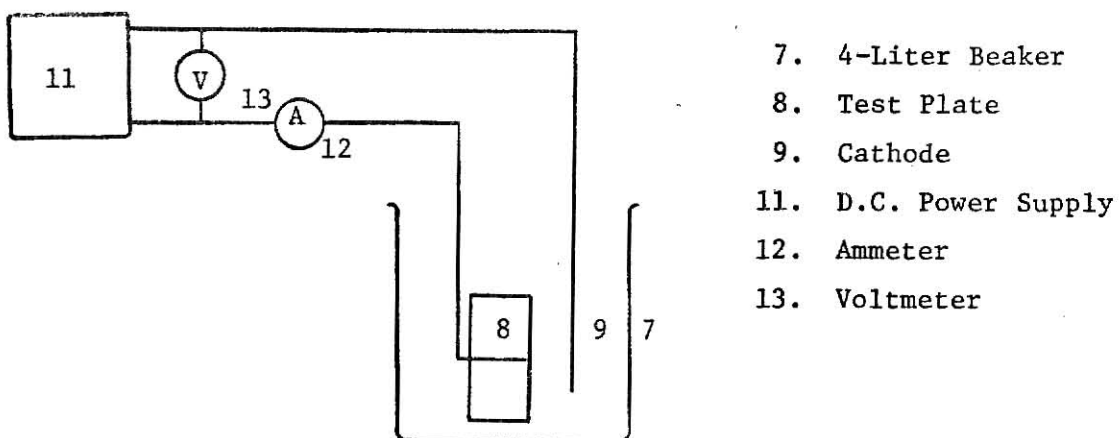

7. 4-Liter Beaker
8. Test Plate
9. Cathode
11. D.C. Power Supply
12. Ammeter
13. Voltmeter

Figure 4. Current Measurement Group

Experimental Test Procedure

The ECL solution was mixed in a 4 liter beaker according to the pro-
portions given in Table 1-a or 1-b depending on which working solution was
to be studied, and then allowed to approach room temperature. Then the test
plate was placed into the solution 3/4" from the bottom of the beaker. Two
liters of the solution were mixed so the top edge of the test plate would be
covered by 3/4". The cathode and thermocouple were inserted into the solu-
tion and the entire system was allowed to reach equilibrium. It made no
difference where the cathode was located as long as the entire platinum
part was submerged and it in no way interferred with the flow. Care was
taken to place the thermocouple approximately 1/2" from the beaker wall and
normal to the test plate.

The temperature was then measured for the ECL solution and the test
plate surface. These temperature measurements agreed to ± 0.5 F before a
test run was started. After these preliminary steps were completed, the
electrical power was applied to the heater core and a potential was applied
through the ECL solution. Again the temperatures were allowed to stabilize
before proceeding. It was observed that initally and for a brief period of
time, the current through the ECL solution varied. But after approximately
one minute the current reached a constant value. This was due to some tran-
sient effect inherent in the reaction at the anode. The value of current
through the ECL solution was not recorded until it stabilized, which was
accepted as an indication that steady state conditions prevailed. Then the
temperatures of the bulk ECL solution were recorded and the current through the
solution was recorded. The procedure described above was carried out for four
different ECL solution potentials, .6, .8, 1.0 and 1.2 volts. At each potential

Table 1

Electro Chemiluminscent

Solution Composition

Water		Distilled and degased
Luminol	150 mg/1 $(4.4 \times 10^{-3}N)$	
H_2O_2	5 ml/1 $(8.5 \times 10^{-4}N)$	Oxidizing Agent
KOH	.56 g/1 (0.01 N)	Adjusts pH, Luminol exhibits Chemiluminescence above pH 9 only.
KCL	74.56 g/1 (1.0 N)	Supporting electrolite
EDTA	Trace	Ties up impurities (should only be used if bulk glow appears upon mixing).

Table 1-a

Methanol		Degased
Luminol	150 mg/1 $(4.4 \times 10^{-3}N)$	
H_2O_2	5 ml/1 $(8.5 \times 10^{-4}N)$	Oxidizing Agent
Tetramethyl Ammonium Chloride	110.0 g/1 (1.0 N)	Supporting Electrolite
Tetramethyl Ammonium Hydroxide	0.91 g/1 (0.01 N)	Adjusts pH of solution

Table 1-b

the current through the solution was recorded. After the current through the
ECL solution was recorded for each of the four ECL solution potentials the
temperatures were again measured. If the temperatures of either the test
plate surface or the ECL solution did not differ from the first readings by
more than 1 F and the temperature difference between the test plate surface
and the ECL solution was the same as before, the data were considered good.
Then the next higher heat input level was set and the procedure described
above was repeated. A total of six levels of heater input was used. The
order of applying the voltages through the ECL solution was varied for each
heater input level to decrease the possibility of any systematic error in-
volved with this phase of the experiment.

A summary of test conditions is shown in Table 2.

Table 2

Summary of Test Conditions

	H_2O	CH_3OH
Energy to heater core, watts	2.34 to 102.24	2.34 to 102.24
Potential through ECL solution, volts	.6, .8, 1.0, 1.2	.6, .8, 1.0, 1.2
GrPr	5×10^6 to 5×10^8	1×10^8 to 4×10^9
Plate surface temperature, F	63 to 114	57 to 130
Bulk temperature, F of ECL solution	58 to 65	51 to 64

To determine if the normality of the tetramethyl ammonium (TMA) chloride,
which served as the supporting electrolite, had any effect on the results,
four concentration levels were tested: .25, .50, .75 and 1.0 normal. The en-
tire aforementioned procedure was carried out for each concentration level.

EXPERIMENTAL RESULTS

AND DISCUSSION

The original data and results are included in Appendix A. Errors in measured values and uncertainty in the calculated results are discussed in Appendix B.

In this study two ECL solutions were used. They were a solution using water and one using methyl alcohol, and are more fully described in Table 1. Problems arose when using the water mixture that could not be overcome. When applying a heater input to the test plate and a potential through the ECL solution gas bubbles collected on the anode, insulating part of it from the ECL solution. This caused the current measurements to vary a great deal for the same conditions on different runs. It was thought that the facilities for vacuum boiling were not sufficient to degas the water thoroughly. Also due to the differences in physical properties, of methyl alcohol and water, higher Grashof numbers could be obtained for the same heater input level for methyl alcohol. Another favorable property of methyl alcohol was the fact that luminol dissolves more completely and readily in it than in water. For these reasons the results for water are not discussed here.

The gross heat transfer results are presented first. The power input to the heater core was determined from

$$q = (I)(E)(3.413) \qquad [2]$$

The average film heat transfer coefficient was then determined from equation [1]. From this average film heat transfer coefficient the average Nusselt numbers were calculated. All the physical properties for Gr, Pr and

Nu were evaluated at the arithmetic mean temperature between the test plate surface and the bulk ECL solution and assumed to be those of methanol.

Figure 5 shows the heat transfer results of this experiment. The curves in Figure 5 are graphs of the equation

$$Nu = 0.555(GrPr)^{1/4} \qquad [3]$$

for the laminar range, and

$$Nu = 0.0210(GrPr)^{2/5} \qquad [4]$$

for the turbulent range, which are accepted correlations for the condition of the present work as given by, for example, Kreith (8). The majority of the experimental values are higher than the curve, but this was expected as end effects were neglected in this study and the true plate temperature was somewhat higher than the measured value due to the method of attachment of the thermocouple. The actual temperature measured was between the true plate surface temperature and the temperature of the ECL solution next to the plate. It was thought that the true surface temperature was close to the measured temperature since the data points on Figure 5 agree closely with equation [3] and [4].

Since mass transfer and heat transfer are analogous phenomena, it was e expected that a log-log plot of measured current through the ECL solution, I, versus (GrPr) should follow equation [3] and [4]. Figure 6 is a log-log plot of I, the current through the ECL solution, versus GrPr for methyl alcohol in the laminar range. It can be seen in Figure 6 that the current is a function of (GrPr) raised to a power

$$I \ \alpha \ (GrPr)^b \qquad [5]$$

The curves in Figure 6 were fitted to the data points by a least square analysis. The slope of these curves is not .25 as was expected if current were to vary directly as the heat transfer coefficient according to equation [3]. The slopes for curves 1, 2, 3 and 4 are .15, .11, .12 and .15 respectively. This

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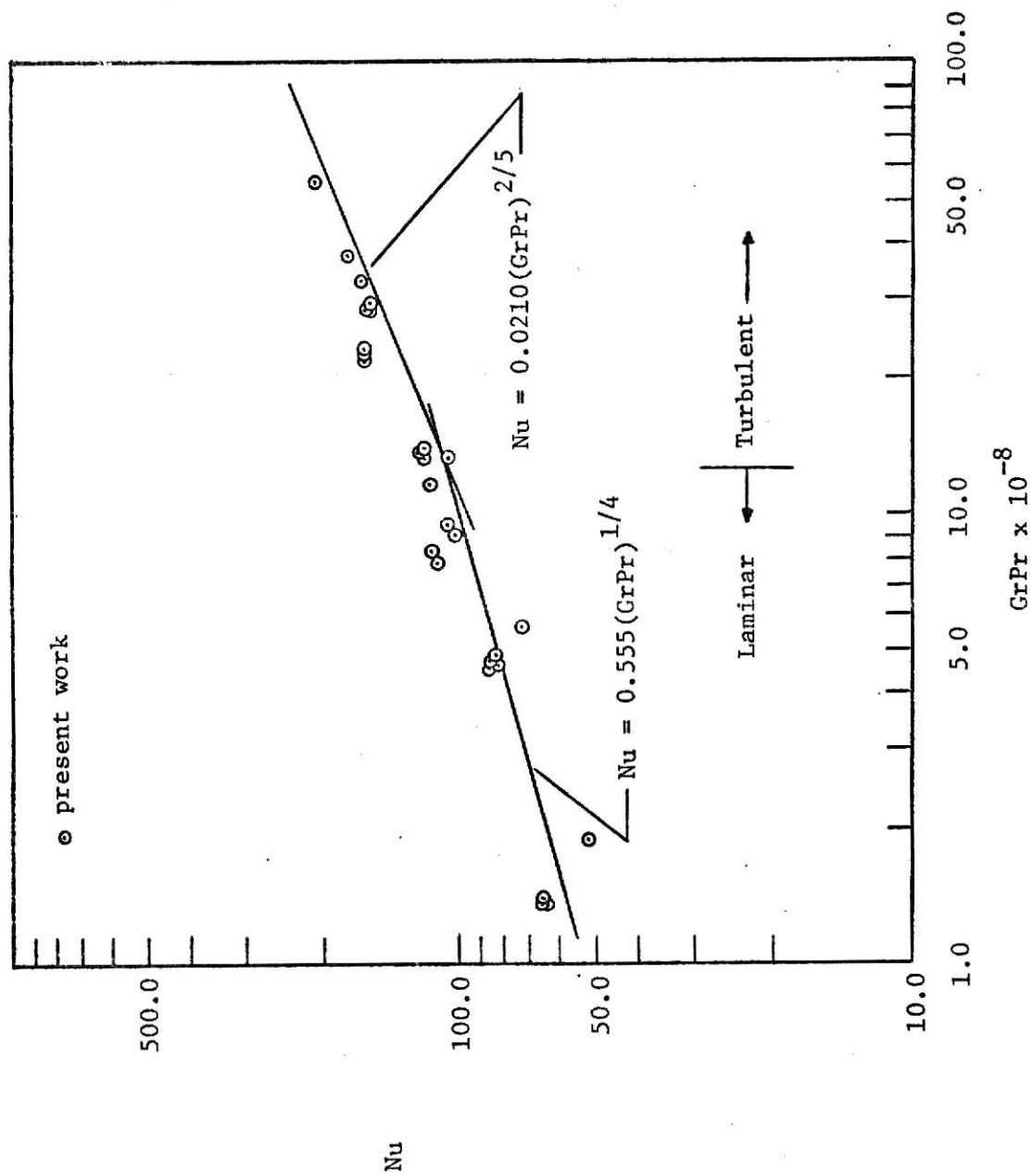INFORMATION ON
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Figure 5. Gross Heat Transfer Results

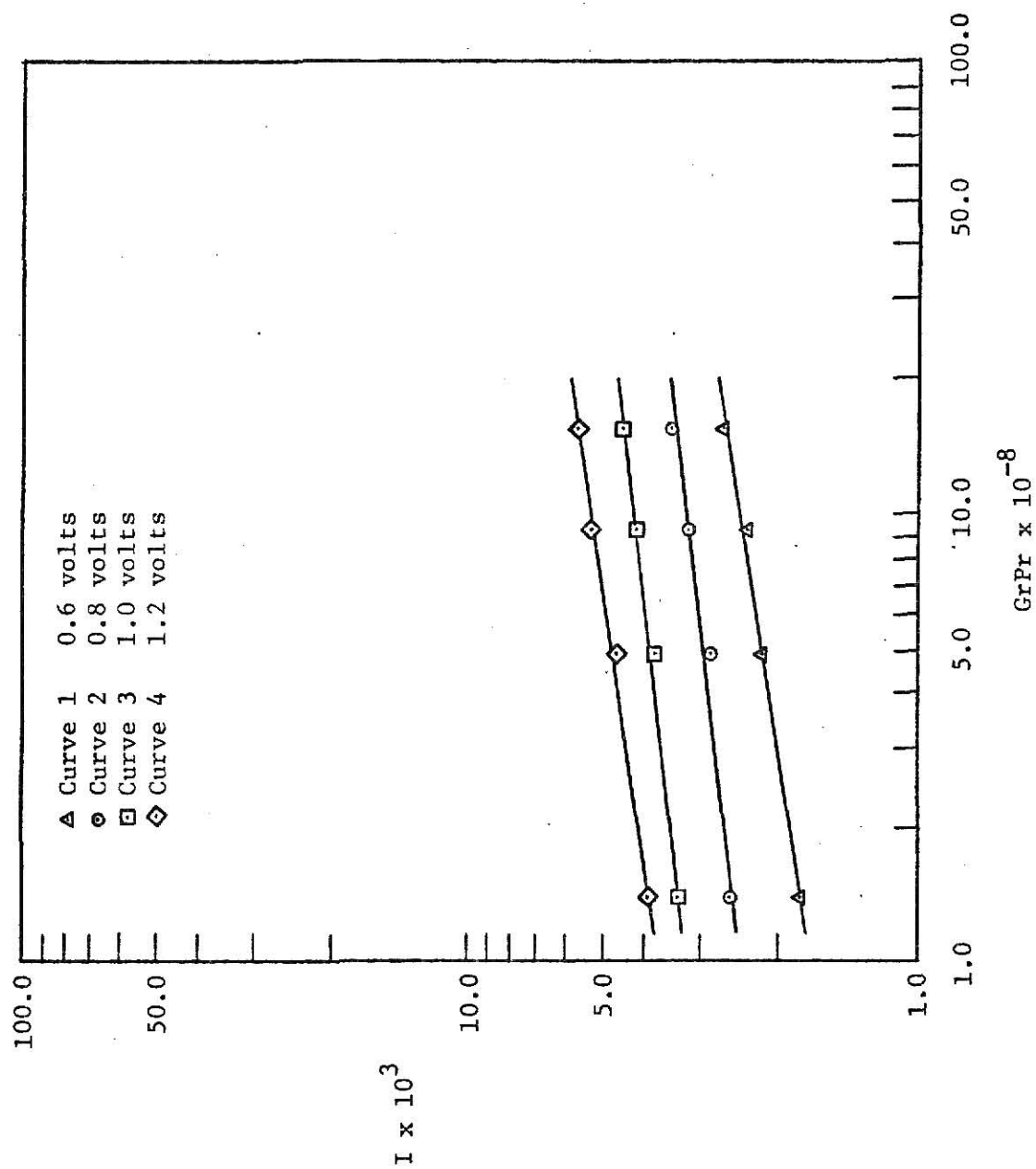Figure 6. Variation of current with GrPr for four anode to solution
voltages in the laminar range.

would suggest that the current through the ECL solution and therefore the ECL reaction is governed by the same laws as natural convective heat transfer but that the current does not increase at the same rate as does the heat transfer.

The local film heat transfer coefficients were calculated from Eckerts equation [Ref. (8)]:

$$h_{cx} = 0.508 \frac{K}{X} [\frac{Pr}{.952+Pr} Gr_x Pr]^{1/4} \qquad [5]$$

because the local value of the natural convective heat transfer coefficient is difficult to measure experimentally. X was the distance from the leading edge of the test plate to the point at which the local value was desired, and the Grashof numbers were evaluated at the same point. Figure 7 shows a plot of h_{cx} versus I, the current through the ECL solution for a 1 normal solution of methyl alcohol in laminar free convection. The curves drawn through the data points were fitted using a least square technique. The fact that the data points are grouped closely to the curves shows that there is definitely a relationship between the local heat transfer film coefficient and the current through the ECL solution. Curves 1 and 2 are nearly parallel which seems to show an independence of voltage in the relationship of h_{cx} to I in the range of .6 to .8 volts. The fact that curves 3 and 4 are not parallel to 1 and 2 suggests that somewhere between .8 and 1.0 volts the relationship of h_{cx} to I is affected by the potential applied through the ECL solution. Springer found that when an anode to ECL solution potential was above 1.2 volts the glow left the surface of the anode. This would suggest that the ECL reaction extended further out into the solution and therefore the reaction rate was affected. The value of I, as was expected, increased as h_{cx} increased because, in laminar natural convection, as the heat transfer
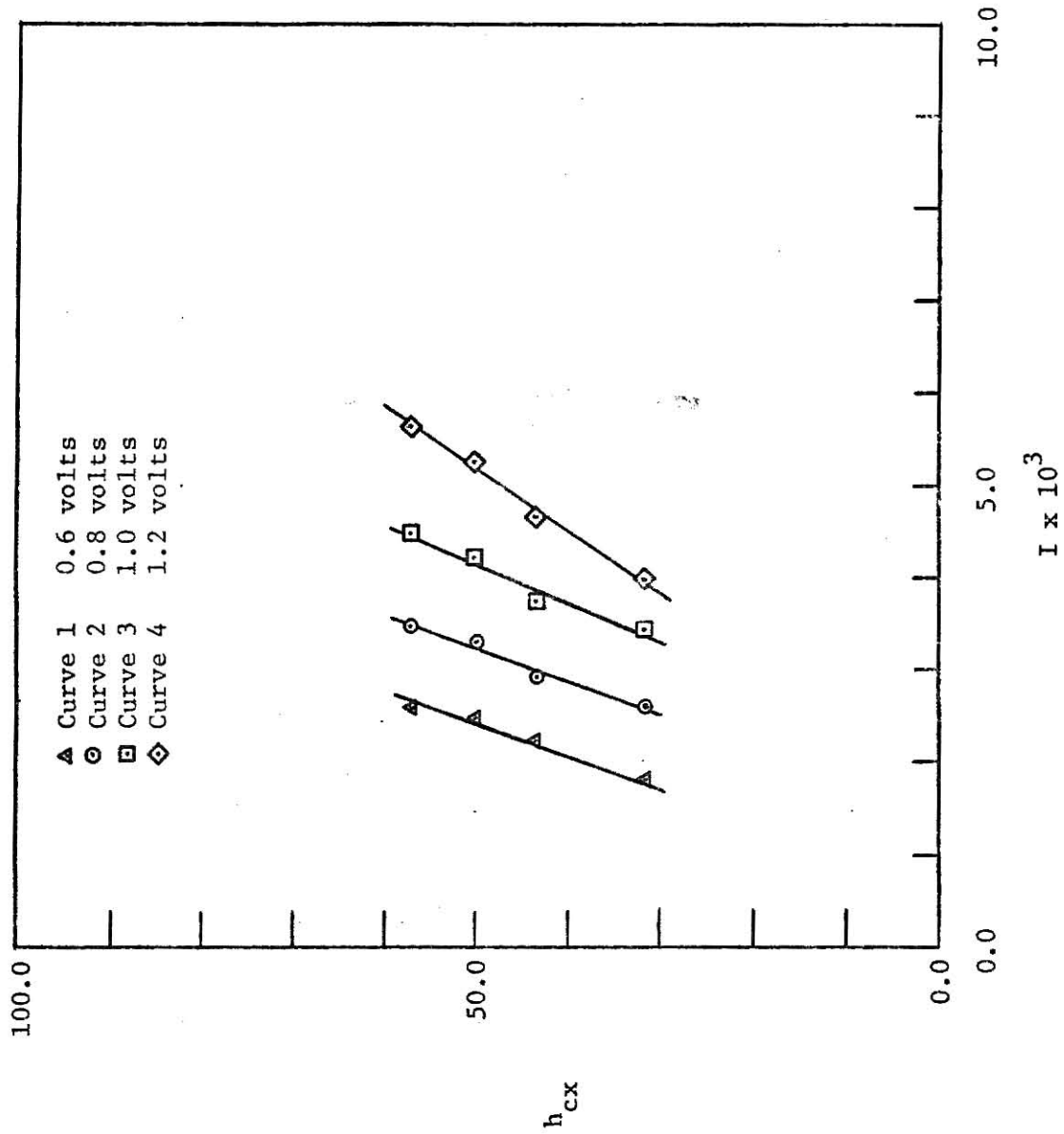
Figure 7. Variation of current with local free convective heat transfer coefficients for four anode to solution voltages in the laminar range.

rate increases, h_{cx} increases and the velocity of the fluid next to the plate increases. Therefore the rate at which the reactants arrive at the anode is increased. And when the rate of the reaction increases so does I. Although this study was mainly concerned with local values a plot was made of measured average film heat transfer coefficients versus the current, I, through the ECL solution, shown in Figure 8. It is interesting to note that the same general trend, of the slopes of the curves, shows up in this figure also. This was expected because the local film heat transfer coefficient increases with GrPr in the same manner as the average value.

All of the results thus far discussed were for laminar free convective flow. To determine if the turbulent range could be detected using ECL several test runs were made at higher values of GrPr. The results are shown in Figure 9 with a log-log plot of I versus GrPr. The curves were drawn through the data points free-hand. Figure 9 shows a definite break in the curves that occurs at approximately 2.2×10^9. The region of transition from laminar to turbulent flow is defined by Kreith (8) to be such that $10^8 < \text{GrPr} < 10^{10}$. The results shown in Figure 9 suggest that the fluid motion is no longer fully laminar at the breaking point. The trend follows that defined by Kreith (8).

Figure 10 is a plot of h_{cx} versus I for methyl alcohol at higher values of GrPr. The curves were drawn in free-hand. There is a definite break which occurs at a GrPr value of 2.2×10^9. The h_{cx} values in the laminar region were calculated from equation [5]. McAdams (9) recommends for turbulent flow that local value for the free film coefficient are the same as the average value so the h_{cx} values in the turbulent range and were obtained from equation [1].

Figure 8. Variation of current with average free convective heat transfer coefficients for four anode to solution voltages in the laminar range.

Figure 9. Variation of current with GrPr for four anode to solution voltages in both the laminar and turbulent ranges.
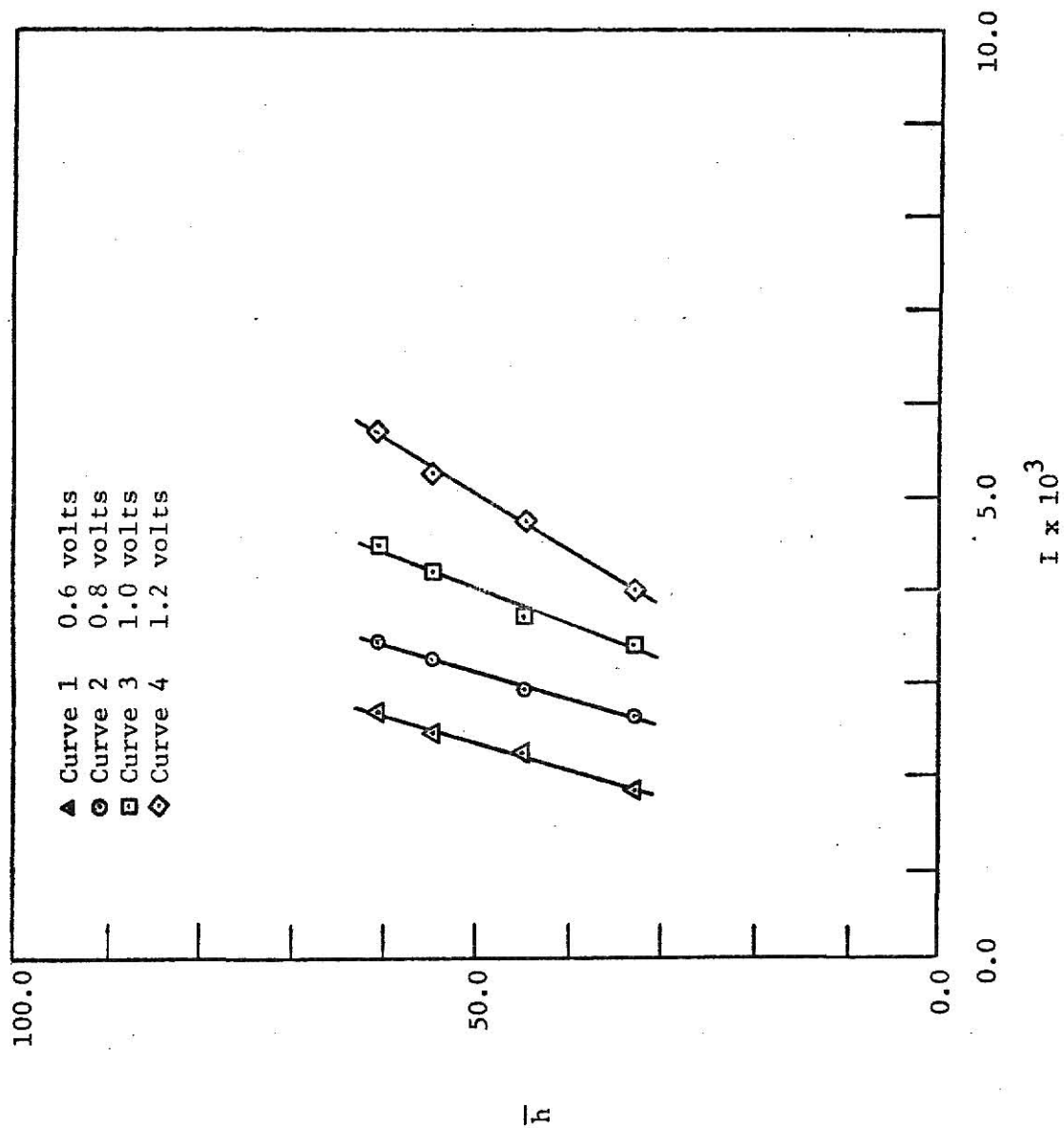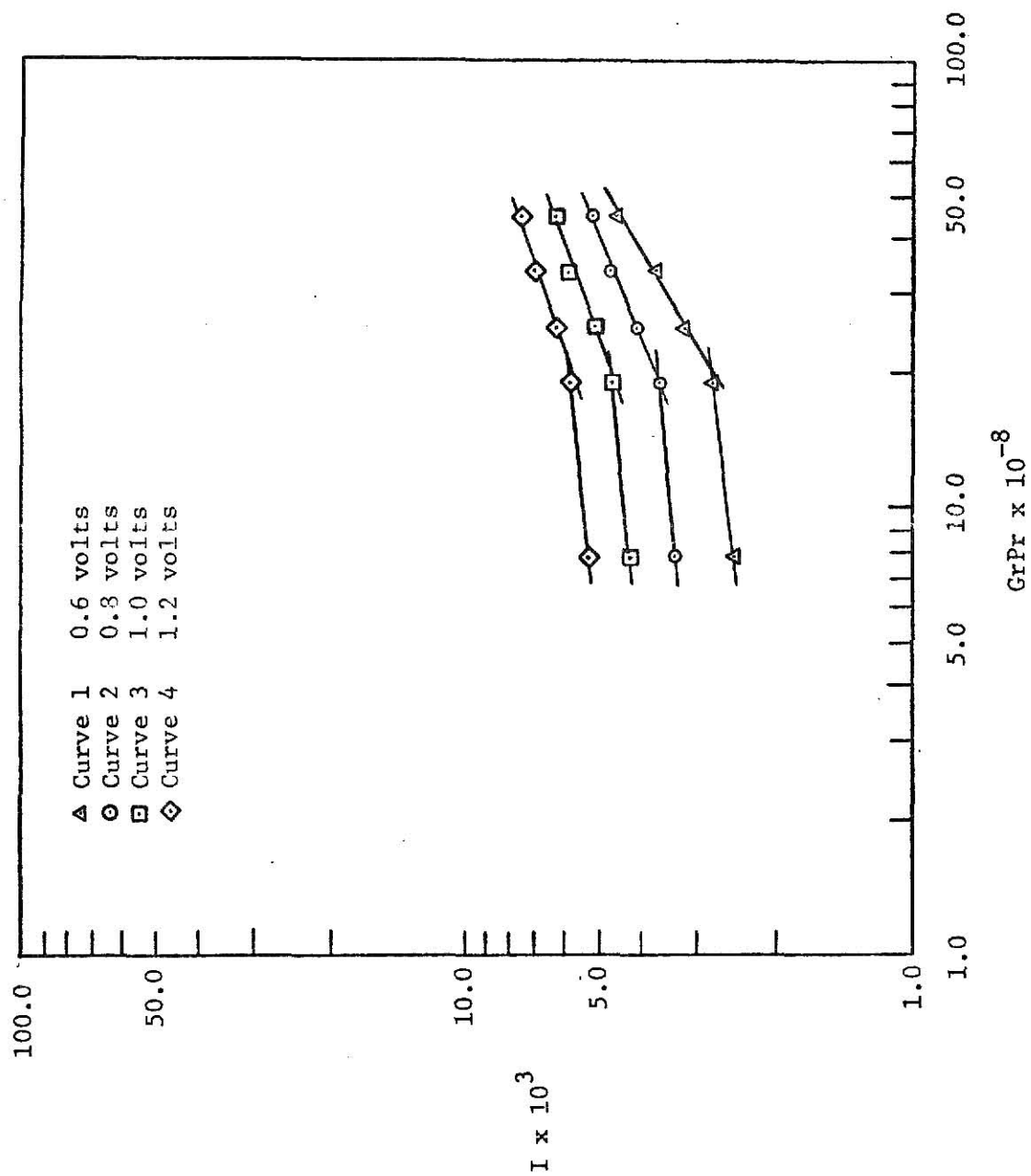
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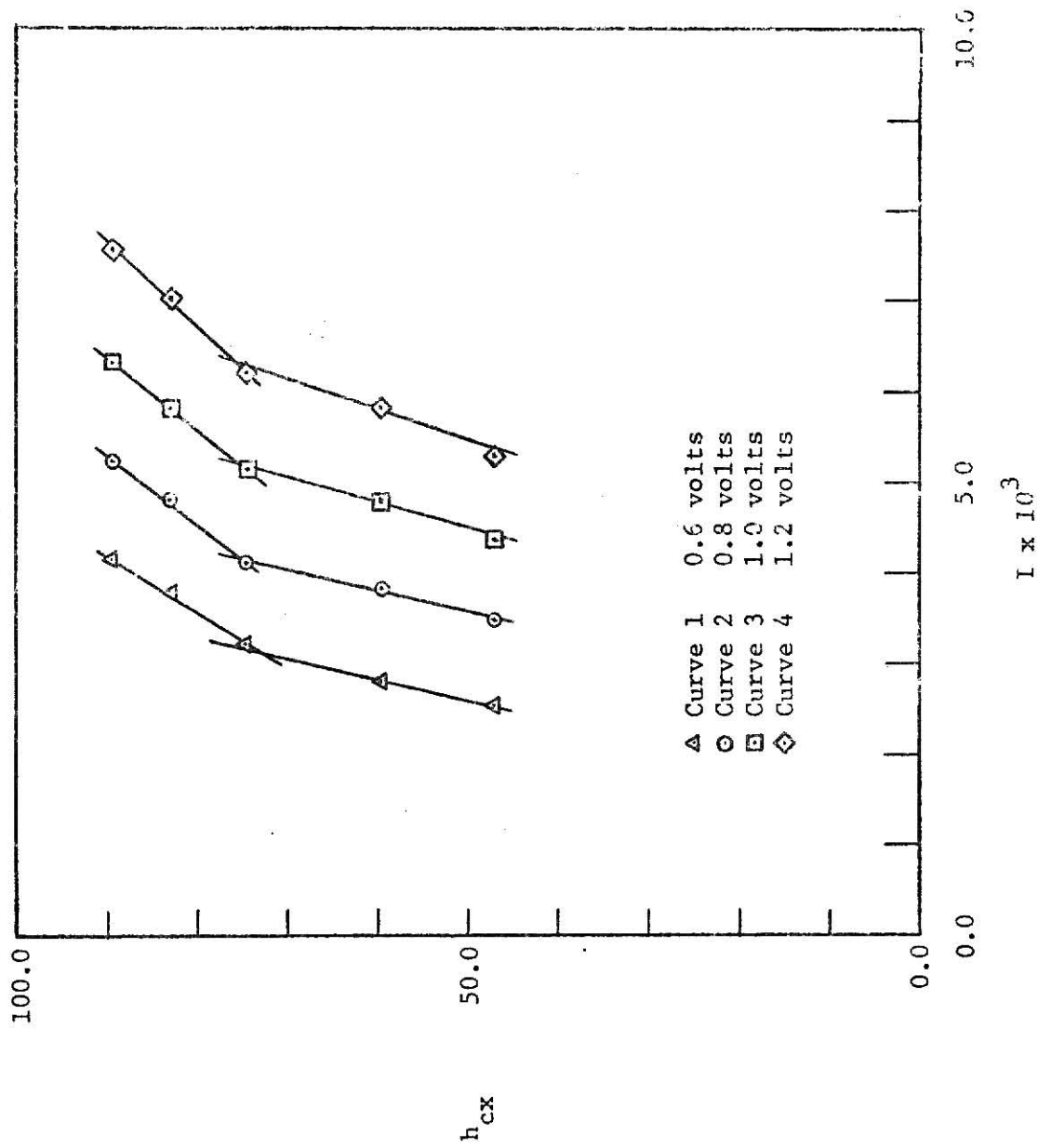
Figure 10. Variation of current with local free convective heat transfer coefficients for four anode to solution voltages in both the laminar and turbulent ranges.

The increased rate of I in the turbulent range can be explained by an increased rate of reactants arriving at the anode due to the mixing caused by turbulence and an increased fluid velocity near the plate.

To determine if the normality of the TMA cloride, which served as the supporting electrolite, had any effect on the results, four concentration levels were tested: .25, .50, .75 and 1.0 normal. The conductivity of the solutions for two different values of GrPr shown in Figure 11. This conductivity is nearly constant over the ranges of ECL solution potentials applied and (GrPr) studied. The close grouping of the points shows that the normality of the TMA cloride makes little difference in the conductivity of the ECL solution in the range from .25 to 1.0 normal.

Figure 11. Variation of current with anode to solution voltages for four tetramethyl ammonium cloride normalities.

CONCLUSION

As a result of the experimental work it was found that:

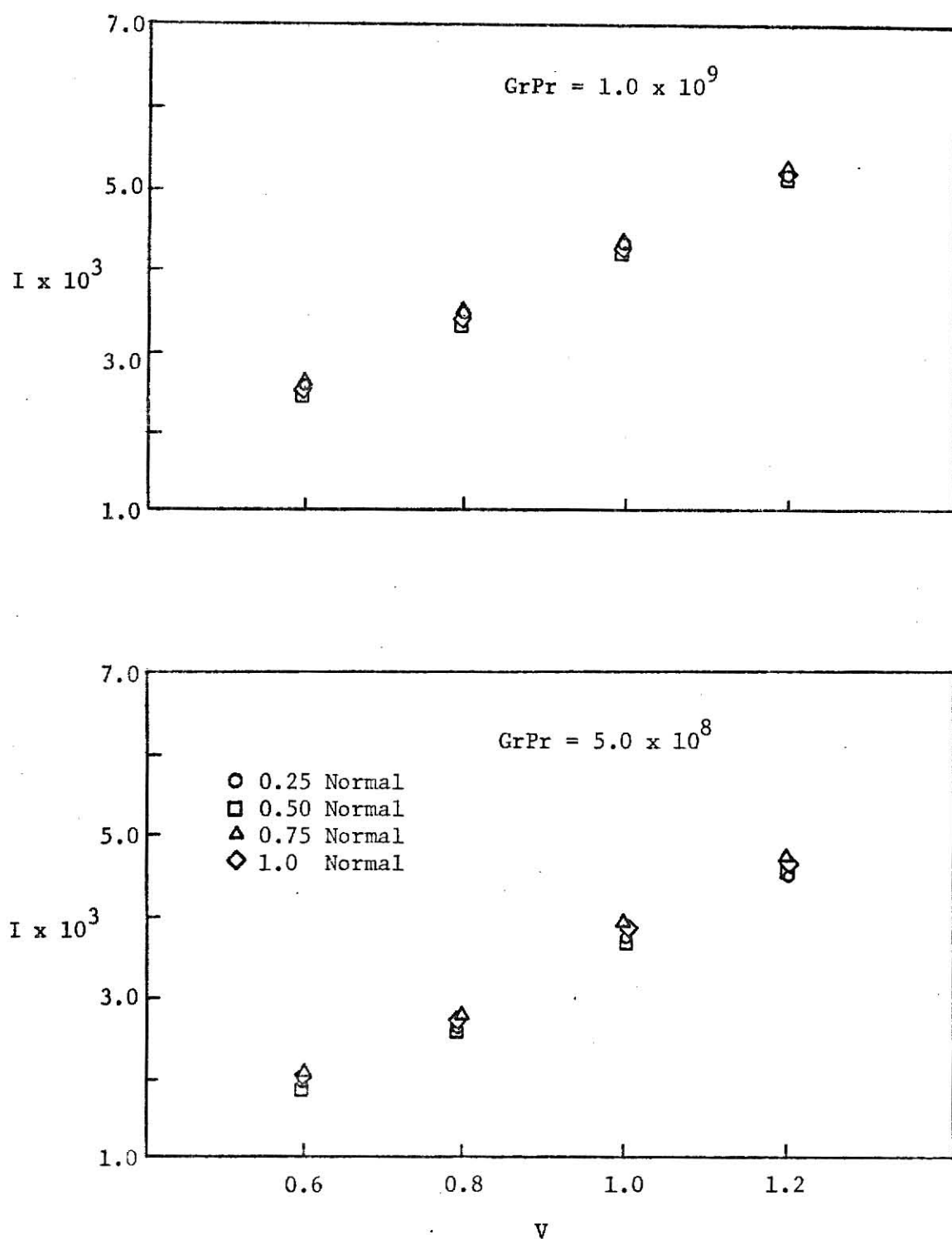1. There is a definite relationship between the current through the ECL solution and the local values of natural convective heat transfer.

2. While the measured current through the ECL solution does follow the same basic laws governing natural convective heat transfer no quantitative relationship could be obtained from this study.

3. The definite relationship not only holds true in the laminar range but apparently will also hold true in the turbulent range.

4. The normality of TMA chloride makes no apparent change in the conductivity of the ECL solution in the range of 0.25 to 1.0 normal.

5. Degassing the ECL solution before use is important in obtaining quality results.

6. There is sufficient evidence in this study that the ECL process could be used to evaluate local values of convective heat transfer rates and to visualize flow at the same time.

7. There is no relationship between the voltage applied through the solution and the h_{cx} versus I curves in the voltage range of 0.6 to 0.8 but at higher values the applied voltage does affect h_{cx} versus I.

RECOMENDATIONS

In all the work done in this area to date with the exception of the present work, the investigations dealt only with the light intensity of the reaction at the anode. The mass transfer rate and by analogy the heat transfer rate was very closely related to the light intensity. A further investigation is needed to discover how the light intensity varies with the current through the solution. Also in this investigation only one size anode was used. Anodes of various surface areas should be used to determine if the current through the solution varies with surface area. Also a better method for attaching the thermocouple to the plate surface is needed. An investigation to determine if the reaction rate is temperature dependent would be desirable.

This investigation could also be extended to include heat transfer in flow. It has strong possibilities for further applications where flow visualization and heat transfer evaluation are needed simultaneously. Although to maximize this application a general equation that would correlate the electrochemilumiscent reaction to the heat transfer rate would be needed.

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APPENDIX A

WATER

.25 Normal KCl

Volts	Current				
.6	5.1	5.3	5.4	5.7	5.8
.8	6.7	6.8	6.9	7.3	7.5
1.0	7.7	8.3	8.5	8.8	9.0
1.2	8.8	9.4	9.6	10.1	10.1
Gr x 10^{-6}	3.6	6.6	12.0	35.0	68.8
Pr	7.43	7.22	6.82	6.11	5.38
$\overline{h}$	58.2	89.8	104.8	90.8	96.2
Nu	42.8	66.0	77.0	66.8	70.7

.50 Normal KCl

Volts	Current					
.6	3.7	4.4	4.6	5.2	5.4	5.7
.8	4.3	5.3	5.9	6.5	7.0	7.3
1.0	4.8	6.2	7.1	7.7	8.6	8.9
1.2	5.2	6.9	8.1	8.8	10.0	11.0
Gr x 10^{-6}	.67	5.8	10.6	13.9	35.3	64.8
Pr	7.75	7.45	7.3	6.89	6.00	5.34
$\overline{h}$	63.8	40.3	59.9	92.2	86.5	101.4
Nu	45.6	28.8	44.0	67.8	63.6	72.4

.75 Normal KCl

Volts	Current					
.6	4.5	4.9	4.9	5.2	5.4	5.7
.8	5.4	6.1	6.2	6.6	7.1	7.3
1.0	5.9	7.3	7.4	7.9	8.4	8.8
1.2	6.0	8.0	8.5	9.0	9.9	10.7
Gr x 10^{-6}	.77	3.15	7.56	11.8	27.96	97.99
Pr	7.38	7.15	6.82	6.57	5.97	4.83
$\overline{h}$	63.8	74.8	89.8	121.3	110.1	88.5
Nu	45.6	53.45	66.0	89.2	80.96	65.1

1.0 Normal KCl

Volts	Current					
.6	3.8	4.9	5.4	5.2	5.5	5.7
.8	4.4	6.1	6.9	6.7	7.2	7.4
1.0	4.8	7.0	8.2	8.1	8.7	9.0
1.2	5.1	7.5	9.3	9.4	10.2	10.5
Gr x 10^{-6}	1.24	3.54	8.47	12.1	29.4	50.7
Pr	7.3	7.1	6.7	6.3	5.82	5.5
$\overline{h}$	42.6	74.8	89.8	128.1	113.6	129.7
Nu	30.4	53.5	66.0	94.2	83.5	95.4

METHYL ALCOHOL

.25 Normal TMA Cl

Volts	Current				
.6	1.5	2.6	2.8	3.2	3.6
.8	2.0	3.4	3.6	4.2	4.7
1.0	2.7	4.3	4.6	5.3	6.0
1.2	3.4	5.1	5.5	6.3	7.2
$Gr \times 10^{-7}$	2.62	12.7	17.97	31.5	49.0
Pr	7.4	7.1	6.9	6.7	6.0
$\bar{h}$	22.4	50.3	68.8	72.2	80.9
Nu	44.7	100.6	137.5	144.4	161.8

.50 Normal TMA Cl

Volts	Current			
.6	1.9	2.0	2.4	2.8
.8	2.6	2.8	3.2	3.7
1.0	3.5	3.7	4.3	4.7
1.2	4.6	4.8	5.4	5.8
$Gr \times 10^{-7}$	6.99	11.2	21.6	35.1
Pr	7.1	7.0	6.6	6.2
$\bar{h}$	41.6	59.9	62.9	73.7
Nu	83.24	119.7	125.7	147.4

.75 Normal TMA Cl

Volts	Current			
.6	1.9	2.3	2.6	3.0
.8	2.7	3.0	3.3	3.9
1.0	3.5	3.9	4.2	4.9
1.2	4.1	4.9	5.2	5.9
$Gr \times 10^{-7}$	1.92	6.71	11.9	22.4
Pr	7.2	7.0	6.9	6.5
$\bar{h}$	33.55	44.8	54.65	62.85
Nu	67.1	89.65	109.31	125.7

1.0 Normal TMA Cl

Volts	Current			
.6	1.9	2.2	2.4	2.7
.8	2.7	2.9	3.2	3.5
1.0	3.4	3.8	4.2	4.5
1.2	4.0	4.7	5.3	5.7
$Gr \times 10^{-7}$	1.97	6.9	13.6	23.6
Pr	7.1	7.0	6.7	6.4
$\bar{h}$	33.6	44.8	54.7	61.1
Nu	67.1	89.7	109.3	122.3

APPENDIX B

ERROR AND UNCERTAINTY ESTIMATION

Temperature

Both thermocouples were calibrated with a set of precision mercury-in-glass thermometers. The precision thermometers had a manufacturer's certi-fied accuracy generally better than ± 0.1 F. The temperature indicated by the bulk fluid thermocouple differed from that of the precision thermometer by -0.1 to + 0.1 F over the temperature range of interest. Therefore, all readings taken from this thermocouple were considered good to ± 0.1 F. The difference between the plate surface thermocouple indications and those of the precision thermometers varied from 0 to + 3.5 F over the range of inter-est. The plate surface temperature readings were not corrected from the cali-bration curve because the method of attachment, as described in chapter 3, was thought to give a reading that was lower than the actual plate surface temperature. These two errors tended to counteract one another. For that reason the error in the plate surface temperature could not be determined with a great deal of certainty but was estimated to be no worse than ± 2% of temperature read which was the error obtained from calibration.

Both temperatures were allowed to vary, at the most, 1 F. In all test runs where the temperature did vary, they varied in the same direction, usually higher. At the same time the difference between the two was not allowed to vary. The uncertainty in the average temperature was just the rms error

$$\sigma = \sqrt{(0.005)^2 + (0.02)^2} = 0.0202$$

ACKNOWLEDGEMENT

Therefore, the average temperature had an estimated uncertainty of $\pm$ 2.02%
of temperature. The uncertainty in the measurement of the temperature dif-
ference between the plate surface and the bulk fluid was estimated to be no
greater than $\pm$ 2.02% of difference.

Uncertainty in the Current and Voltage of

the Electrical Input

The voltmeter was calibrated against a voltmeter with a manufacturer's
guaranteed accuracy of $\pm$ 0.05% of reading for the lowest value of voltage
used. These two systems varied randomly, but by no more than 1% of reading.
The maximum error which could reasonably by expected would be the rms error:

$$\sigma_V = \sqrt{(0.0005)^2 + (0.01)^2} = 0.01$$

On a percentage basis $\pm$ 1%.

The ammeter was calibrated against an ammeter with a manufacturer's
guaranteed accuracy of $\pm$ 0.2% of reading for the lowest value of current
used. These two systems varied randomly, but by no more than 1.5% of
reading. The maximum error which could reasonably be expected would be

$$\sigma_I = \sqrt{(0.002)^2 + (0.015)^2} = 0.0152$$

The uncertainty on a percentage basis was $\pm$ 1.52%.

Total Uncertainty in Electrical Input

The sensitivity factors were calculated to be:

$$S_I = 1$$
$$S_V = 1$$

The uncertainties in the current and voltage were:

$$\sigma_I = 0.0152$$

$$\sigma_V = 0.01$$

Thus, the uncertainty in electrical input was

$$\sigma = \sqrt{(1)^2(0.0152)^2 + (1)^2(0.01)^2} = 0.0182 \text{ or } 1.82\%$$

Uncertainty in Anode to ECL Solution Current

The ammeter used had a manufacturer's certified accuracy of $\pm$ 3% of reading and could be read to the nearest 0.0001 ampere. For the lowest value of current read the uncertainty was

$$\sigma = \sqrt{(0.0054)^2 + (0.03)^2} = 0.031 \text{ or } 3.1\%$$

Uncertainty in the Convection Coefficient

The convection film coefficient is defined by

$$\bar{h} = \frac{q}{A(T_s - T_\infty)}$$

The uncertainty depends on both q and $(T_s - T_\infty)$. The sensitivity of these two quantities are

$$S_q = 1$$

$$S_{(T_s - T_\infty)} = 1$$

Thus, the uncertainty is

$$\sigma_{\bar{h}} = \sqrt{(0.0182)^2 + (0.0202)^2} = 0.028 \text{ or } 2.8\%$$

Uncertainty in the Nusselt Number

Compared to the uncertainty of the film coefficient, the uncertainties in 1 and K are negligible. Thus, the uncertainty in the Nusselt number is the same as that in the film coefficient.

Uncertainty in the Grashof Number

Compared to the uncertainty of the temperature difference, the uncertainties in g, β, ρ, 1 and in μ are negligible. Thus, the uncertainty in the Grashof number is the same as that in the temperature difference.

Uncertainty in the Prandtl Number

The Prandtl number is defined by

$$Pr = \frac{C\mu}{K}$$

where all three factors were evaluated at the average temperature. The only uncertainty involved was in the temperature at which the three factors were evaluated. They are

at 60 F

$$\sigma_C = 0.002$$
$$\sigma_K = 0.001$$
$$\sigma_\mu = 0.001$$

$$\sigma = (0.002)^2 + (0.001)^2 + (0.001)^2 = 0.0025 \text{ or } .25\%$$

at 100 F

$$\sigma_C = 0.002$$
$$\sigma_K = 0.001$$
$$\sigma_\mu = 0.0015$$

$$\sigma = \sqrt{(0.002)^2 + (0.001)^2 + (0.0015)^2} = 0.0027 \text{ or } .27\%$$

It can be seen that the uncertainty in the Prandtl number is very small.

VITA

WILLIAM A. SMILEY III

Candidate for the degree of
MASTER OF SCIENCE

THESIS: An Electrochemiluminescent Heat Trasnfer Analogy

MAJOR
FIELD: Mechanical Engineering

BIOGRAPHICAL:

Personal Data: Born in Arcadia, Florida, June 13, 1949, the only
son of Dr. William A. and Virgina L. Smiley.

Education: Graduated from Goodland High School, Goodland,
Kansas in May 1967; received the Bachelor of Science
degree from Kansas State University with a major in
Mechanical Engineering, in December, 1971; com-
pleted the requirements for the Master of Science
degree in Mechanical Engineering in May, 1973.

Professional
Experience: Was employed as an undergraduate research assistant
by the Applied Mechanics Department at Kansas State
University, Manhattan, Kansas from May, 1970 to
December, 1971; was a graduate research assistant in
the Mechanical Engineering Department at Kansas State
University from January, 1972 to May, 1973; was em-
ployed by Smith and Boucher in Mission, Kansas as a
design engineer from May, 1972 to September, 1972
and from December, 1972 to January, 1973.

AN ELECTROCHEMILUMINESCENT HEAT TRANSFER ANALOGY

by

WILLIAM A. SMILEY III

B.S., Kansas State University, 1971

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ABSTRACT

An electrochemical system suitable for evaluating the heat transfer rates and visualizing flow simultaneously is described. When two electrodes are submerged in a flow field of a chemiluminescent solution and a potential is applied between them a reaction occurs at the anode producing a blue glow. This process is known as an Electrochemiluminescent reaction. For a given solution and potential, the reaction at the anode is governed solely by the mass transfer and, by analogy, the heat transfer. Experimental results are presented, for natural convection from a vertical plate, showing a relationship between the current through the system and the heat transfer rates. Several parameters were varied and their effect are also discussed.