Indian Institute of Technology Gandhinagar

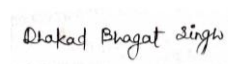
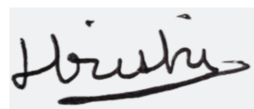
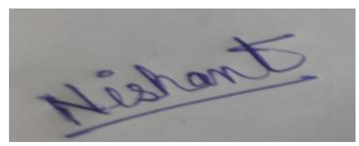
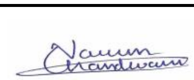
NUKIYAMA’s BOILING EXPERIMENT

ES 311 Project Report

26th November 2022

Under the guidance of

Prof. Soumyadip Seth

Group member name	**Signature**
Anavart Pandya(Group Leader)	
Aravind Krishna	
Dhakad Bhagat Singh	
Hrishikesh. C.P	
Kareena Beniwal	
Nishant Singh Tomar	
Manav Gadpale	
Shreevadsa A M	
Tanvi Dixit	
Varun Chandwani	
Yash Khandelwal	

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1) Abstract

In the fast-growing world, thermal management is one of the crucial aspects to look upon. We always wish for maximum output with minimal possible input.

As a part of this project, we aim to transfer large amounts of heat with a small temperature difference between the heated surface and the fluid(water), and that’s where the Pool Boiling phenomenon comes in.

Since Nukiyama was the first to come up with major observations on pool boiling, it is also known as Nukiyama’s Boiling. Pool boiling is a phenomenon that happens when a pool of liquid is heated from a surface. The phenomenon is mainly the evaporation that occurs when the surface temperature exceeds the saturation temperature of the liquid. In such a case, vapour bubbles form at nucleation sites on the surface, then grow in size and gradually detach from the surface. The heated bubbles then traverse to the surface through convection. S Nukiyama, in 1934 did pioneering research in the field of boiling.

2) Introduction

Pool boiling occurs when a pool of liquid is heated from a surface. We will investigate the pool boiling of water at atmospheric pressure, being heated by an immersion heater with water at a subcooled temperature. We would attempt to determine subcooled pool boiling heat transfer characteristics* and the critical heat flux (CHF) condition.
We will be experimenting with different types of wires based on dimensions to perform this experiment. We would also be closely observing the bubble dynamics (and film occurrence) that would be taking place on the surface of the wire.

Generally, four regions are observed in pool boiling:
Which are:

1. Natural Convection
2. Nucleate Boiling
3. Transition boiling
4. Film boiling

Natural convection occurs when no bubbles are formed.

In nucleate boiling, bubbles start forming, heat transfer occurs through bubbles and natural convection, and flux increases to its maximum value, Critical Heat flux.

Wherein in Transition Boiling, the bubble formation is so rapid that a vapour film begins to form near the surface of the wire.

And finally, film boiling occurs where flux increases as the temperature increases. Here the heat transfer from the surface of the wire to water happens through conduction and radiation through the vapour film formed. As the temperature increases, the contribution due to radiation in the heat transfer becomes more significant.

Nucleate pool boiling of liquid mixtures, when extrapolated, can be used to study the boiling of mixtures of organic and inorganic nature instead of the boiling of pure components as done currently. These analyses can provide us with results which are of considerable practical importance. Thus, it has many applications in the chemical and petrochemical processing industry, like boiling multicomponent liquid mixtures. This can also be used in thermal plants and cooling systems as we need a working fluid capable of reducing energy losses in heat exchanges.

3) Problem Statement

Our goal is to obtain the critical heat flux characteristics and compare them with Sir Nukiyama's Boiling experiment. We will investigate the pool boiling of water at atmospheric pressure, heated by an immersion heater.

We would attempt to determine subcooled $pool\ boiling\ heat\ transfer\ characteristics\ *$and critical heat flux (CHF) conditions. The power input to the wire (and thus flux) would be varied by changing the voltage with the help of a variac. We will be experimenting with different types (based on dimensions) of wires to perform this experiment.

As an add-on, we would be closely observing the bubble dynamics (and film occurrence) taking place on the surface of the wire or upwards.

$*\ pool\ boiling\ heat\ transfer\ characteristics$: A plot between heat flux through wire and ΔT, where ΔT is the temperature difference between wire and that of water (close to the surface of the wire).

4) Governing equations and other parameters/assumptions

- The resistance of the wire = R, where R = $\rho\frac{L}{A}$ (L = length of the wire, A = surface area = πDL, D = diameter of the wire, ρ = resistivity of the wire)
- Here ρ is a function of temperature. The value of ρ different temperatures is directly used from the data provided on the internet.
- The resistance of the screws = r (measured value = 1 ohm)
- ∴ Total resistance = R + r
- Voltage provided measured across the ends of the wire + screw system = V
- Current passing through the wires = i = $\frac{V}{R+r}$
- Power generated in the wire due to the current = P = i^2R
- The flux generated in the wire = Q = $\frac{P}{A}$

5) Experimental Method

(i) Materials Used:

- **a)** BoroSilicate Beaker: This experiment required the presence of water as a surrounding liquid around various heating coils and elements, and for this, a storage tank was a must required component which in this case was the borosilicate beaker. We chose this as its melting temperature was higher than the temperature range of our experiment.
- **b)** Immersion Heater: This experiment was performed at water temperatures much higher than the normal room temperature. This was achieved by using an immersion heater of power 1000W.
- **c)** Temperature Controller: In our experiment, we must keep varying the water temperature for different readings. So, for this reason, we purchased this as our immersion heater didn't have an inbuilt temperature controller.
- **d)** Variac: A variac consists of a range of output voltages, which indirectly will lead to varying flux. It was used to get variable heat flux output from the nichrome wire.
- **e)** Nichrome (32, 36, 38 and 42 gauge): This experiment required a metal surface which can conduct electricity at high temperatures without melting. High temperatures were necessary to observe the process of bubble formation. Hence, different diameter nichrome wires were used to observe the same phenomena.
- **f)** Copper wire: To study the effect of other conducting materials for Nukiyama's Boiling phenomenon, we used copper wire of 36 gauge diameter.
- **g)** LED Light & Camera: They were necessary to observe the bubble formation more precisely.
- **h)** Thermocouple: Continuous temperature feedback was required to note the various critical temperature points while performing the experiment.
- **i)** Stand: This was built to hold the immersion rod/heater at a certain height above the beaker.
- **j)** Acrylic Set-up: It was manufactured to hold the copper screws.
- **k)** Stainless-steel Screws: They acted as a connecting link between variac wires and nichrome wire and served the purpose of a wire fixture.

(ii) Experimental Setup: Experimental setup consists of the following components:
A Stand was manufactured to hold the immersion rod and an acrylic set-up containing the wires for the connections. A beaker filled with water is placed beneath the stand. The immersion rod was connected to the temperature controller. The immersion road was then held with the help of the stand and placed inside the beaker to vary the water temperatures (above room temperature). The temperature controller's end (that measured the temperature at every instant) was then placed in the water to control the temperature. Variac was used to provide the different voltage outputs to the nichrome and copper wires (on which experiments were carried out) through the connecting wires, placed with the help of stainless-steel screws. So, variac was responsible for varying the flux through the wire. Nichrome wires provided us with the metal surface to observe the bubble formation. An acrylic glass set-up was also placed just above the beaker to hold the nichrome wire connection set. One end of the thermocouple was then placed near the wire to measure its temperature. A tripod camera was set up to capture the experiment's images and videos. Sufficient lighting was provided by using a led light in front of the setup.

(iii) Experimental Procedure: Experimental procedure was carried out in the following manner-

1. To begin with, we filled the beaker with water to a marked level.
2. Next, we calibrated the positions of the beaker and stood positions so that water reached a level marked on the immersion rod.
3. Then, the nichrome wire was put in between the stainless steel screws, held through the acrylic set-up and put on the top of the beaker. The part of the acrylic set-up containing the screws and nichrome wire was then immersed in the water.
4. Through these stainless steel screws, a series connection of connecting wires was made to the variac to supply the input voltage to the system, which in turn, provided the heat flux to the system.
5. LED light and a USB camera were placed in such a way that we could observe the bubble dynamics/formation in a better way.
6. We kept increasing the voltage until we saw bubbles forming (known as nucleate boiling) near the wire.
7. We noted the point when we first saw bubble formation.
8. Then, we kept increasing the temperature of the wire by increasing the input voltage until we saw the bubble chain. We also noted down this reading
9. Then we again increased the temperature to obtain the Critical Heat Flux (CHF) point, which was the main aim of our experiment.
10. Then, we repeated the same steps for different temperatures and wire gauges.

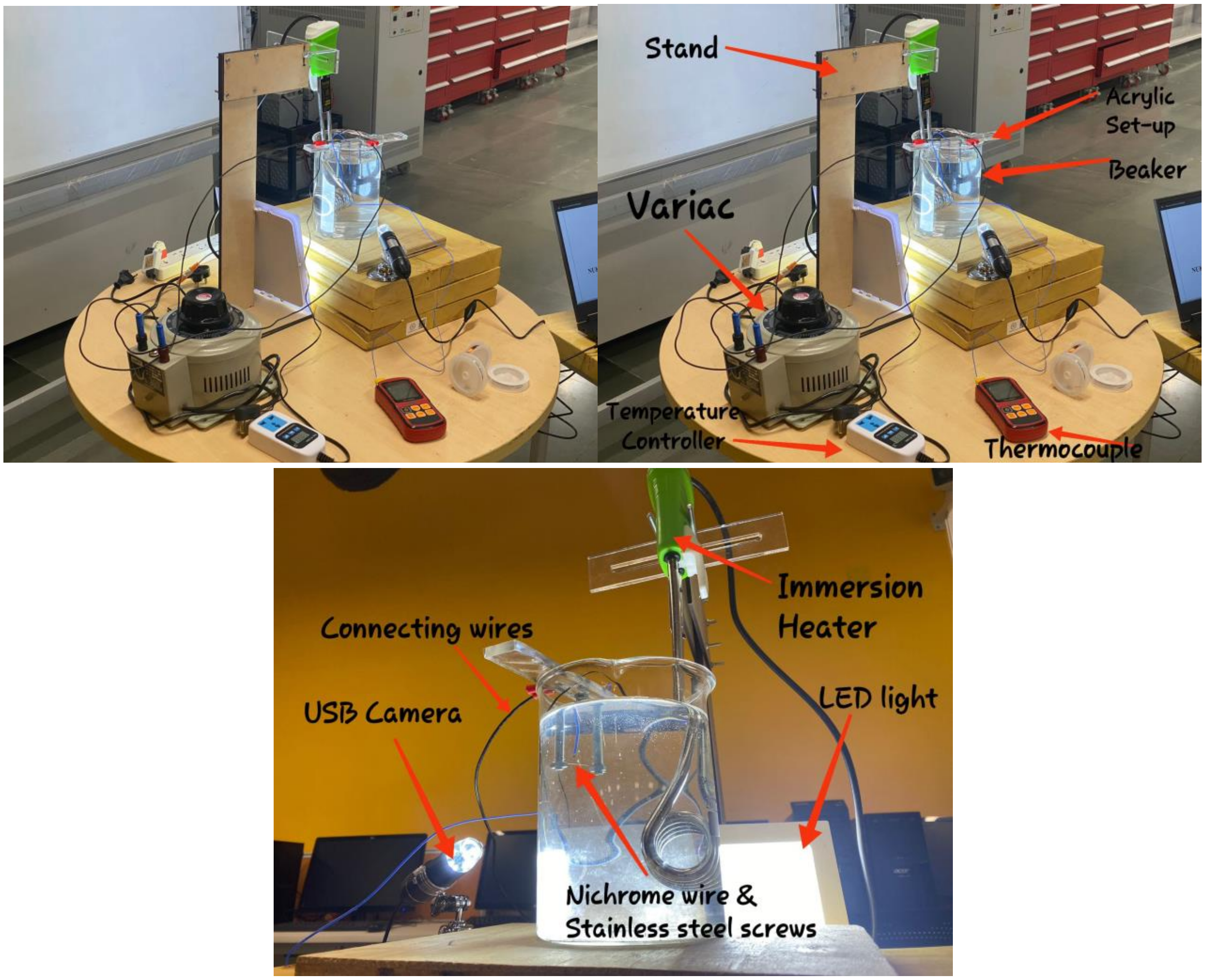


Figure: Images showing the experimental set-up and connections

6) Results:

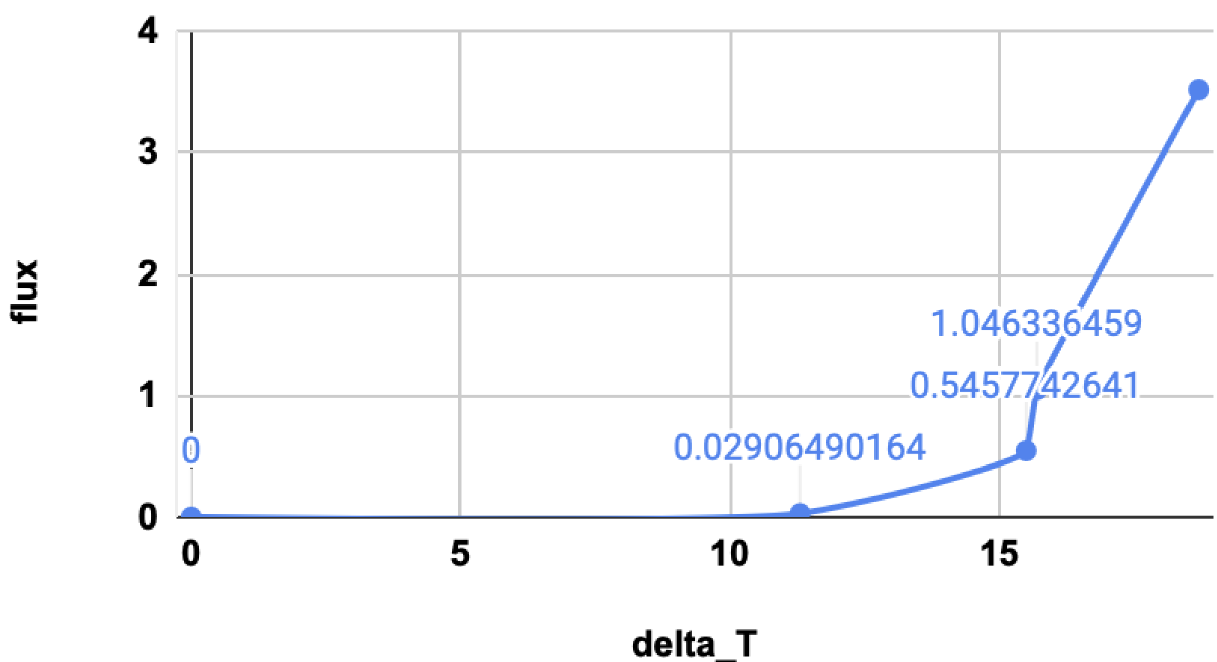
- **42 gauge Nichrome wire**

Length = 6.5cm

T_{water} = 68.3° C

T_{sat} = 100° C

T_wire (℃)	**Vwire** (V)	**Remarks**	**delta_T** (℃)	**Flux** (W/mm²)	**I** (A)	**P** (W)
68.3	0		0	0	0	0
79.6	3		11.3	0.02906490164	0.1407624633	0.4024733189
83.8	13		15.5	0.5457742641	0.6099706745	7.557554545
84	18		15.7	1.046336459	0.8445747801	14.48903948
87	33	CHF	18.7	3.516853098	1.548387097	48.69927159



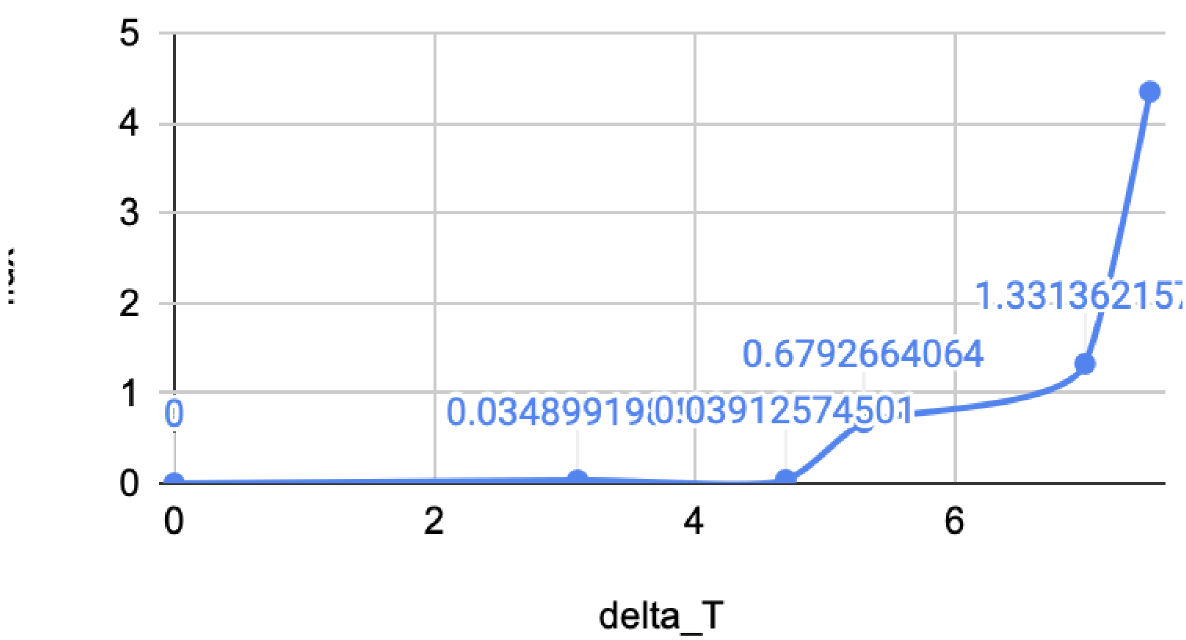
➢ **42 gauge Nichrome wire**

Length = 7 cm

T_{water} = 68.3^o C

T_{sat} = 100^o C

T_wire (℃)	**Vwire** (V)	**Remarks**	**delta_T** (℃)	**Flux** (W/mm²)	**I** (A)	**P** (W)
83	0		0	0	0	0
86.1	3.4		3.1	0.03489919848	0.1486338798	0.483263161
87.7	3.6		4.7	0.03912574501	0.1573770492	0.5417898414
88.3	15		5.3	0.6792664064	0.6557377049	9.406073636
90	21		7	1.331362157	0.9180327869	18.43590433
90.5	38	CHF	7.5	4.359380848	1.661202186	60.36609036



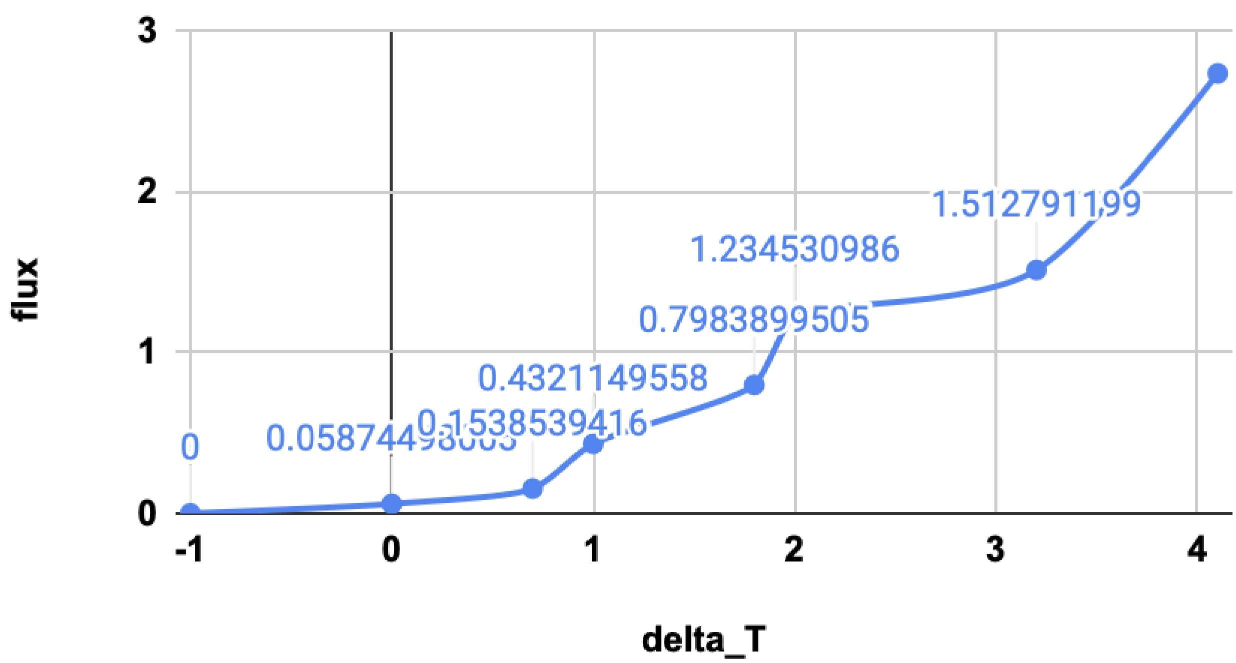
- **42 gauge Nichrome wire**

Length = 8 cm

T_{water} = 99^o C

T_{sat} = 100^o C

T_wire (℃)	**Vwire** (V)	**Remarks**	**delta_T** (℃)	**Flux** (W/mm^2)	**I** (A)	**P** (W)
98	0		-1	0	0	0
99	4.69	onset boiling	0	0.05874498005	0.1803846154	0.8134652367
99.7	7.59		0.7	0.1538539416	0.2919230769	2.130477071
100	12.72	nucleate boiling	1	0.4321149558	0.4892307692	5.983668639
100.8	17.29		1.8	0.7983899505	0.665	11.055625
101	21.5		2	1.234530986	0.8269230769	17.09504438
102.2	23.8		3.2	1.512791199	0.9153846154	20.94822485
103.1	32	CHF	4.1	2.734796603	1.230769231	37.86982249



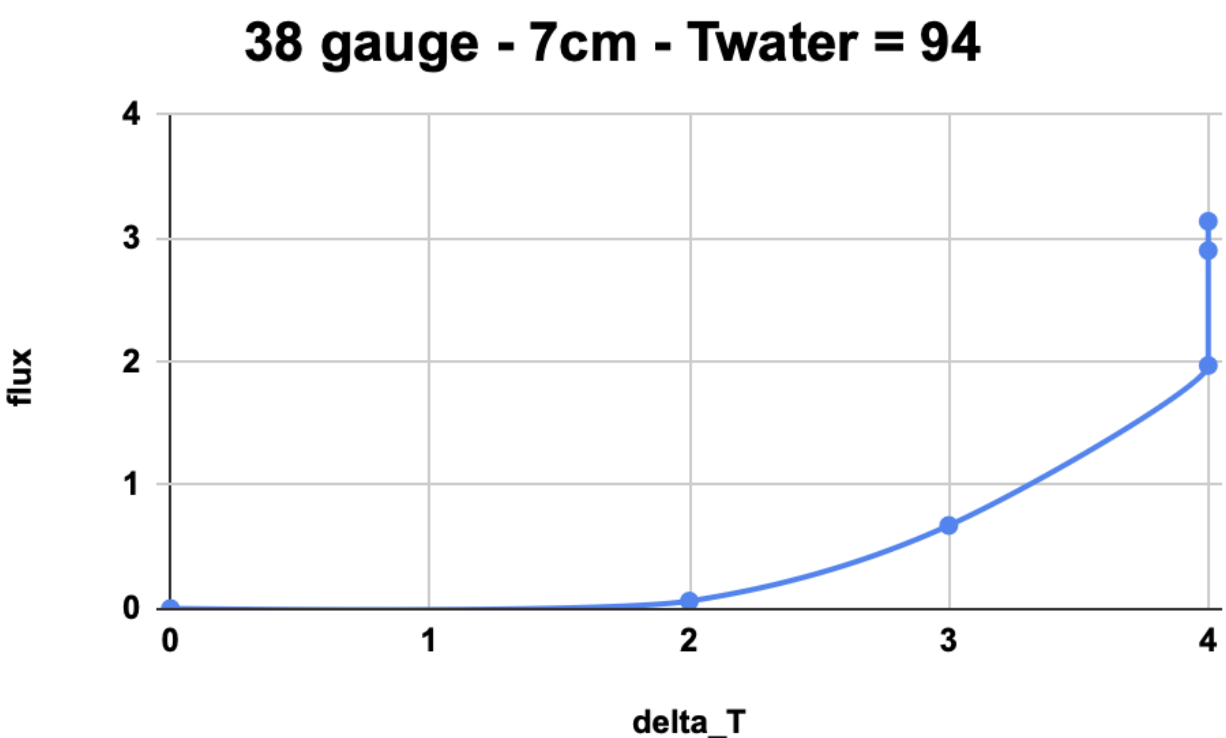
- **38gauge Nichrome wire**

Length = 7 cm

T_{water} = 94 ^oC

T_{sat} = 100 ^oC

T_wire (℃)	**Vwire** (V)	**Remarks**	**delta_T** (℃)	**Flux** (W/mm^2)	**I** (A)	**P** (W)
94	0		0	0	0	0
96	3.6	onset of boiling	2	0.06005417804	0.3692307692	1.329230769
97	12.04		3	0.6717245167	1.234871795	14.86785641
98	20.6		4	1.966403626	2.112820513	43.52410256
98	25	CHF	4	2.896131271	2.564102564	64.1025641
98	26	burnt	4	3.132455583	2.666666667	69.33333333



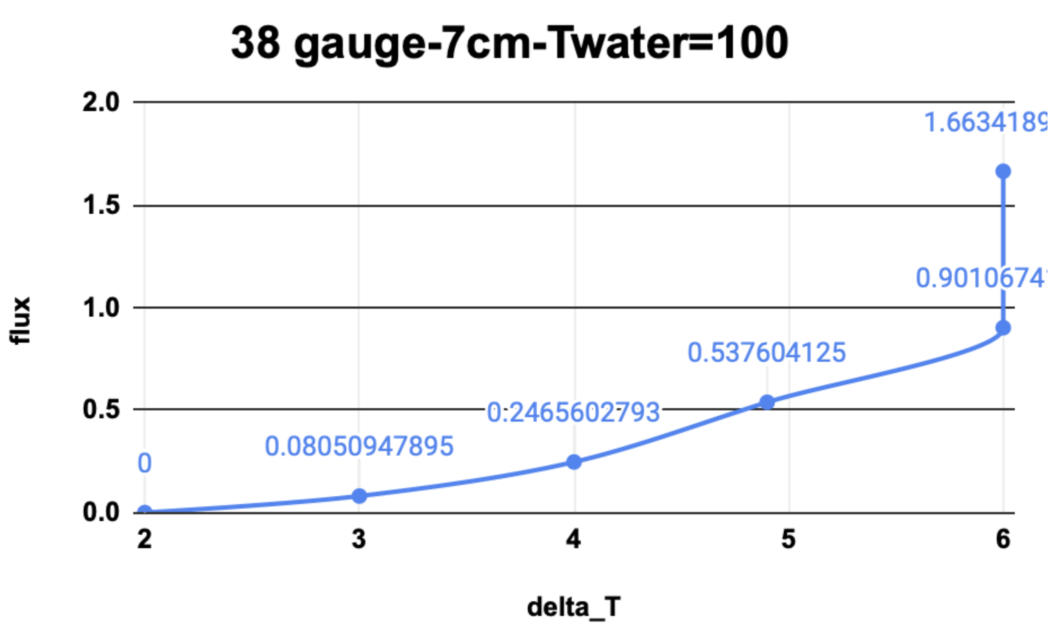
- **38 gauge Nichrome wire**

Length = 7 cm

T_{water} = 100^o C

T_{sat} = 100^o C

T_wire (℃)	**Vwire** (V)	**Remarks**	**delta_T** (℃)	**Flux** (W/mm²)	**I** (A)	**P** (W)
102	0		2	0	0	0
103	4.4	onset of boiling	3	0.08050947895	0.4512820513	1.781985536
104	7.7	nucleate boiling	4	0.2465602793	0.7897435897	5.457330703
104.9	11.37		4.9	0.537604125	1.166153846	11.89925444
106	14.72		6	0.9010674114	1.50974359	19.94409993
106	20	CHF	6	1.663418987	2.051282051	36.81788297
	22	burnt				



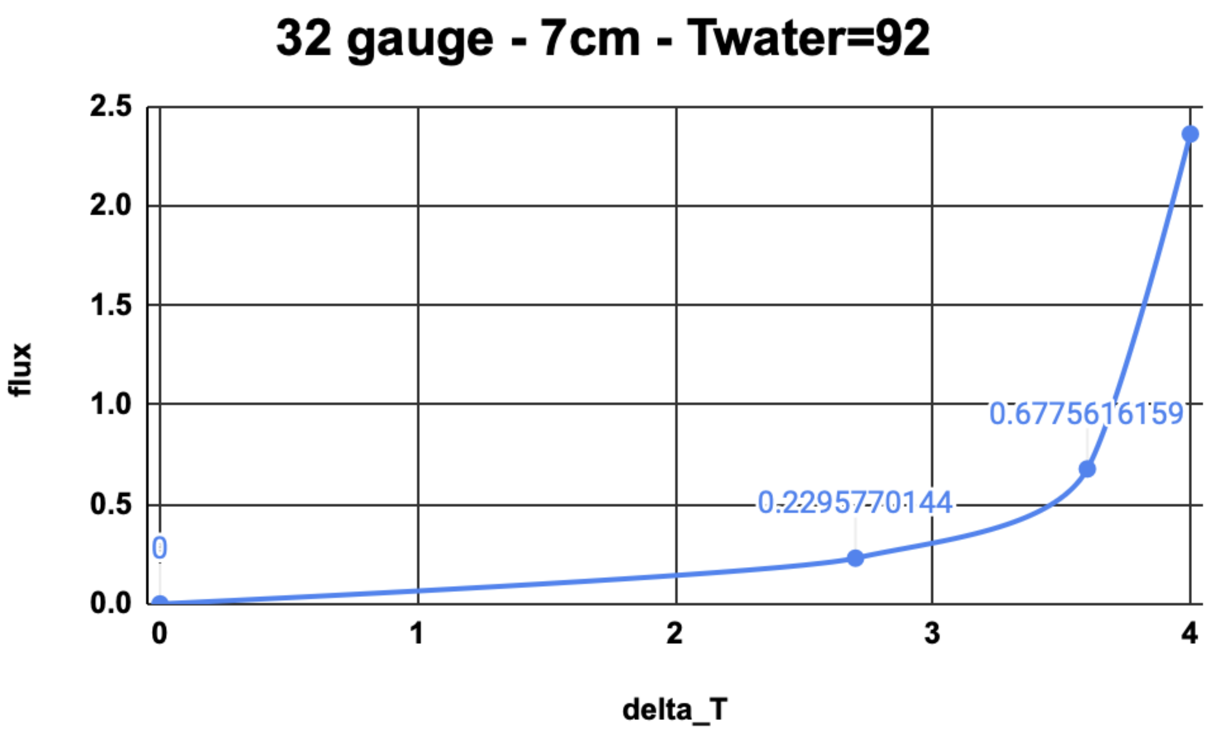
- **32 gauge Nichrome wire**

Length = 7 cm

T_{water} = 92 ^oC

T_{sat} = 100 ^oC

T_wire (℃)	**Vwire** (V)	**Remarks**	**delta_T** (℃)	**Flux** (W/mm^2)	**I** (A)	**P** (W)
92	0		0	0	0	0
94.7	7.8	onset of boiling	2.7	0.2295770144	2.447058824	13.09896194
95.6	13.4	nucleate boiling	3.6	0.6775616159	4.203921569	38.65959246
96	25		4	2.358409501	7.843137255	134.5636294



7) Discussions

1. We got the wires' results until the critical heat flux point (in some cases, we also got one or two more readings after the CHF point). This is due to the surface temperature of the wire, which exceeds its melting point, due to which the material of the wire melts and the wire gets cut.
2. It can be possible to get all the other regions in the graph, including transition and film boiling, if a wire with a very high melting point is taken.
3. The temperature difference (ΔT) in the experimental results is very low compared to the established standard results. This might have occurred due to the thermocouple not showing an accurate surface temperature of the wire due to the effect of the surrounding water temperature.
4. It is difficult to get the transition boiling region by varying flux through the wire. In the transition boiling region, the flux starts to decrease and the surface temperature of the wire increases. Therefore the only way to get this is by controlling the surface temperature of the wire.
5. The point of critical heat flux was observed very clearly in the nichrome wire with the smallest diameter, i.e. the 42 gauge wire. Please note that heat flux is inversely proportional to the surface area (that is proportional to the diameter of the wire) and directly proportional to the cross-sectional area (that is proportional to the square of the diameter of the wire), which is because the flux is inversely proportional to the resistance of the wire (which is inversely proportional to the area of cross-section of the wire). Hence the flux is directly proportional to the wire diameter. Lesser flux means slow heating; hence, we could observe clear points in the smallest diameter wire, the 42 gauge wire.
6. In most of the experiments, after achieving the critical heat flux point, the film boiling starts occurring. Still, plotting those points on the graph was difficult because the film boiling occurred for a very short time, and suddenly, the wire melted.

8) Conclusions

1. As the diameter of the wire increases, the heat flux generated increases. (This is explained in detail in the 5th point of the discussions section (7th section)).
2. The same applies when the wire's length is increased, keeping the diameter constant.
3. As the power input increases, the heat flux increases.
4. Nucleate boiling is an efficient process for removing large quantities of heat from heated surfaces with minimal variation in surface temperature. Since maximum heat flux is achieved in this region.
5. Comparison with Nukiyama's Original Pool Boiling Curve:

   - CHF in Nukiyama's pool boiling curve was obtained at $\Delta T = 30^o$ C whereas we got CHF in $\Delta T = 4^o$ C - 6^o C range (This may be due to the fact that the thermocouple accuracy was not so great).
   - Maximum heat flux obtained from Nukiyama's curve is of the order 10^6 W/m^2, and the same is the case with ours.
   - The nichrome wire in Nukiyama's experiment burnt out at a temperature difference greater than 1000^o C whereas we observed a burnout at a very low ΔT in the range 5^o C - 6^o C.

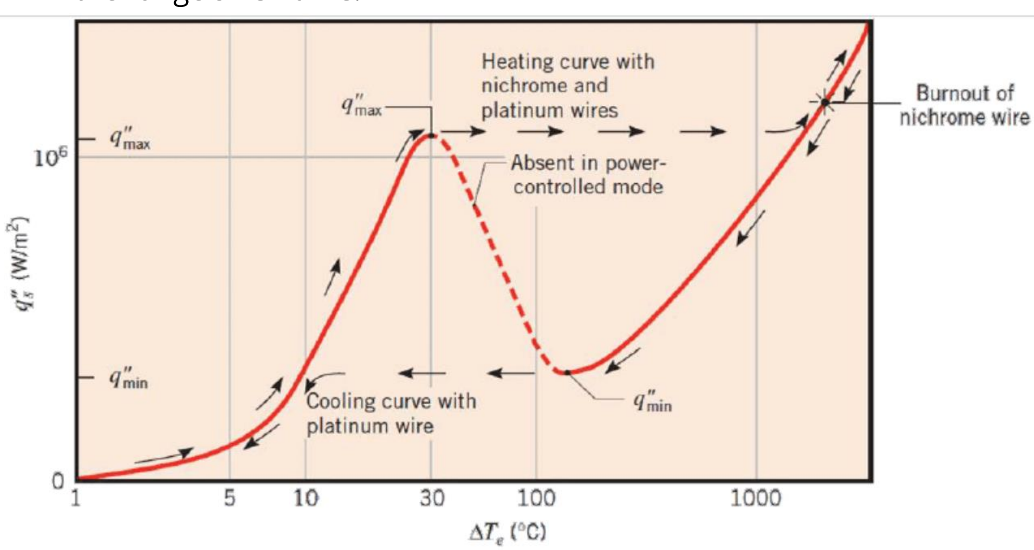


Fig: Nukiyama's boiling curve for water at a pressure of 1 atm

9) Critical analysis

1. Since boiling is a surface phenomenon, efforts could be made to improve the physical and chemical properties of the test wire, such as generating porosity and enhancing wettability which would increase the heat flux obtained.
   Also, the effect of the thermal conductivity of the wire could be studied.
2. Since copper has greater conductivity, copper screws could have been used in place of stainless steel to obtain faster and more efficient heating of the wire.
3. The thermocouples and temperature controllers of better quality can be used to get more accurate readings and maintain the temperature more efficiently.
4. The way of measuring the temperature of the wire can also be improved. The procedure can first measure the resistance of the wire by measuring the voltage across the wire and the current passing through it. Then from the resistance, the resistivity can be obtained. From the resistivity, the temperature of the wire can be determined using the data tables provided on the internet. This method will have a much more accurate reading of the wire temperature compared to the current method, which uses a thermocouple to measure the temperature of the wire.
5. We could not get any readings for copper wire as the copper wire's resistance is too low. In place, other materials, such as tungsten, can be used.
6. Overall, a more precise setup could have been used that is not in direct contact with the environment (e.g., wind, dirt etc.) and human touch to have minimum errors in the readings.

10) Future Work

- The experiment can be done by changing the fluid instead of water and analyzing the heat flux vs temperature difference curve for different wire gauges.
- Since boiling depends on the nature of the surface, different materials of the wire can be used to perform the experiment and compare which one produces the most heat flux.
- The frequency with which bubbles form decreases as bubble size increases, reducing heat transfer. This fact was observed by looking at the bubbles with naked eyes. More such results can be obtained with quantitative analysis (and not just qualitative analysis) if the bubble dynamics are closely observed with tools such as computer vision and machine learning, wherein one can approximate the diameter of the bubble, the rate of bubble formation, the velocity of bubbles and the number of bubbles at a particular instant.
- Particles of an additive, like sodium chloride, accumulate on the heater's surface, forming a layer. It is necessary to determine the thickness of this layer on the heater surface, up to which CHF enhancement can occur. This porous layer prevents the formation of a vapour blanket on the heater surface and breaks up voids close to the heater surface, resulting in CHF enhancement.

11) References

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