ME4442 Heat and Mass Transfer

Semester 8

Hot wire/ film anemometer design

By

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2 Introduction

Hot wire and hot film sensors are used for measurements of fluctuations in the wind [1]. In wind measurements the cooling of a heated wire or film is dependent on the velocity and density of the flow past the wire [1]. These usually consist of a cylindrical quartz or glass core, covered with a nickel or platinum film which is in turn electrically insulated with a very thin quartz or ceramic coating. Both wire and film sensors have been used in the marine atmosphere. Mechanical sturdiness and stability of calibration are usually decisive arguments in Favor of the hot film sensor rather than the hot wire, with its higher frequency response [1].

3 Question and Answer

3.1 Constant temperature hot-wires anemometer.

(a) Constant temperature hot-wire anemometer: The expected velocity measurement range is 1 m/s to 50 m/s. The accuracy of the velocity measurement must be 0.01 m/s. The maximum current allowed to go through the probe is 200 mA. The accuracy of the current measurement sensitivity is 10 μA. Take ambient temperature (Ta) as 27 degrees Celsius. The probe temperature (Ts) should be kept at a value between 1.5-2 times of the ambient temperature (Ts =[1.5-2] *Ta). It is recommended to keep probe diameter smaller than 50 μm for fast operation of the device.

(i) Suggest probe temperature and diameter.

(ii) Provide Current vs velocity graph for the suggested design parameters

Resistivity of Platinum = 0.000000106Ωm [2]

Assignment - 01

a) Constant temperature hot-wire anemometer,

* velocity measure range $1\,ms^{-1}$ - $50\,ms^{-1}$
* Accuracy - $0.01\,ms^{-1}$, max current - 200mA
  accuracy of current sensitivity - $10\,\mu A$
* $T_a = 27^{o}C$, $T_s = [1.5 - 2] * T_a$
* $d < 50\,\mu m$

i) Convection heat transfer on wire,

$$Q = Ah\Delta T$$
$$=$$

$$h = \frac{K}{D}\,\overline{Nu}$$
$$= \frac{K}{D}\left[C (Re)^{n} \cdot P_r^{n} \cdot \left(\frac{P_r}{P_s}\right)^{1/4}\right]$$

$$Q = (\pi D)\left(\frac{K}{D} \times C \times \left(\frac{\rho U D}{\mu}\right)^{n} \times P_r^{n}\left(\frac{P_r}{P_s}\right)^{1/4}\right)\left(T_s - T_a\right)$$

K - conduction heat transfer co-efficient on air,
T_s - Probe Temperature
T_a - ambient temperature.
P_r - Prandlt number at Ambient temperature
P_s - Prandltl number at Surface

Power dissipation on wire

$$P = I^2 R$$

I - Current
R - resistance
P - Power dissipation
ρ - resistivity of
A - Area of crossection
l - length of wire

$$P = I^2 \times \left(\frac{\rho l}{A}\right)$$

$$= I^2 \left(\frac{\rho l}{\pi \left(D^2/4\right)}\right)$$

$\rho = \beta$

In a steady state condition,

$$\dot{Q} = P$$

$$A \left[\frac{K}{D} \times C \times \left(\frac{\rho U D}{\mu}\right)^n Pr^n \left(\frac{Pr}{Ps}\right)^{1/4} (T_s - T_a) \right] = I^2 \left[\frac{\beta l}{\pi (D^2/4)}\right]$$

$$(2\pi r l) \left[\frac{K}{D} \times C \left(\frac{\rho U D}{\mu}\right)^n Pr^n \left(\frac{Pr}{Ps}\right)^{1/4} \right] (T_s - T_a) = I^2 \left(\frac{\beta l}{\pi D^2/4}\right)$$

$$\Rightarrow I^2 = \pi^2 K C \left(\frac{\rho^n U^n}{\mu^n}\right) D^{n+2} Pr^n \left(\frac{Pr}{Ps}\right)^{1/4} (T_s - T_a) \times \frac{1}{4\beta}$$

$$I^2 \propto U^n$$

$$I^2 = \cancel{C_1 U^n}\; C_1 U^n$$

differentiate,

$$2I(dI) = C_1 \times n\, U^{(n-1)} \times dU$$

$$2I(\Delta I) = \frac{I^2}{U^n} \times n \times \frac{U^n}{U} \times \Delta U$$

$$\Delta U \approx \frac{2(\Delta I)\, U}{n I}$$

$$\frac{\Delta I}{\Delta u} = \frac{nI}{2u}$$

current sensitivity $10\,\mu A$, velocity accuracy $-0.01\,m s^{-1}$

$$\Delta I / \Delta u \geq 10^{-3}$$

Re ~~max~~

$$\cancel{2I(dI) = C_1 \times n \times u^{n-1} \times du}$$

$$\cancel{2I(\Delta I) = C_1 \cdot n\,(u^{n-1}) \times du}$$

$$\cancel{C_1 = 2\Delta I / \Delta u}$$

$$I^2 = C_1 u^n$$

$$C_1 = \frac{\left(\pi^2 K C \left(\frac{\rho u D}{\mu}\right)^n P_r \left(\frac{P_r}{P_s}\right)^{1/4} \frac{(T_s - T_a)}{4\beta}\right)}{u^n}$$

$$C_1 = \frac{\pi^2 K C \rho^n D^n}{\mu^n} \times \frac{P_r^{(n+1/4)}}{P_s^{1/4}} \times \frac{(T_s - T_a)}{4\beta}$$

$$2I\,dI = C_1 m \times u^{m-1} \times du$$

$$2I\,\Delta I = C_1 \times m \times u^{m-1} \times \Delta u$$

$$\frac{2I\,\Delta I}{m\,u^{m-1}\,\Delta u} = C_1$$

$$\Delta I/\Delta u \geq 10^{-3}$$ [For the accuracy of velocity $0.01\,ms^{-1}$ and current sensitivity of $10\,\mu A$]

velocity of $50\,ms^{-1}$, $m = 0.4$

$$\frac{m C_1 u^{(m-1)}}{2I} = \Delta I/\Delta u$$

$$\frac{m C_1 u^{m-1}}{2\,\frac{u^{m/2}}{C_1^{1/2}}} \geq 10^{-3}$$

$$\frac{m C_1^{1/2}}{2u^{1-m/2}} \geq 10^{-3}$$

$$C_1 \geq 5.6569 \times 10^{-3}$$

∴ we need to find diameter of wire and probe ~~diameter~~, temperature when $C_1 \geq 5.6569 \times 10^{-3}$ and $I_{max} \leq 200\,mA$

* So $d = 29\,mm$

$T_s = 45^{\circ}C$

3.1.1 Data and Parameters

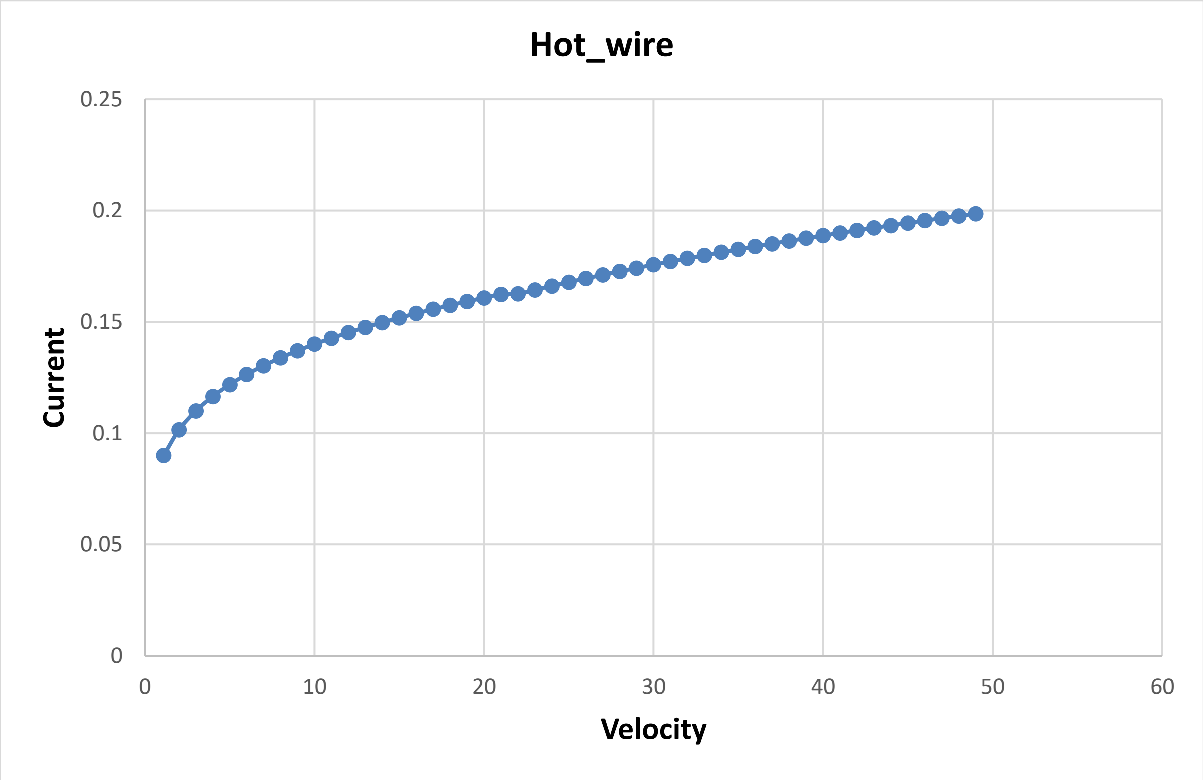
Prs =	0.70448	(assumption)
Pr =	0.707	
n=	0.36	for all Pr<10
Ts =	45	
Ta =	27	
K =	0.0263	
μ =	0.00001846	
ρ =	1.1614	
π =	3.141592654	
Prs	0.707	
D	29	

3.1.2 Calculation

U (m/s)	D (μ m)	Re	C	m	I	dI
1	29	1.824517876	0.75	0.4	0.088335	
1.01	29	1.842763055	0.75	0.4	0.088511	0.000176
1.02	29	1.861008234	0.75	0.4	0.088686	0.000175
1.03	29	1.879253413	0.75	0.4	0.088859	0.000173
1.04	29	1.897498592	0.75	0.4	0.089031	0.000172
1.05	29	1.91574377	0.75	0.4	0.089202	0.000171
1.06	29	1.933988949	0.75	0.4	0.089371	0.000169
1.07	29	1.952234128	0.75	0.4	0.089539	0.000168
1.08	29	1.970479307	0.75	0.4	0.089706	0.000167
1.09	29	1.988724485	0.75	0.4	0.089871	0.000166
1.1	29	2.006969664	0.75	0.4	0.090035	0.000164
2	29	3.649035753	0.75	0.4	0.101471	0.011435
3	29	5.473553629	0.75	0.4	0.110042	0.008571
4	29	7.298071506	0.75	0.4	0.116559	0.006517
5	29	9.122589382	0.75	0.4	0.121879	0.00532
6	29	10.94710726	0.75	0.4	0.126405	0.004526
7	29	12.77162514	0.75	0.4	0.130363	0.003958
8	29	14.59614301	0.75	0.4	0.133891	0.003528
9	29	16.42066089	0.75	0.4	0.137083	0.003191
10	29	18.24517876	0.75	0.4	0.140002	0.002919
11	29	20.06969664	0.75	0.4	0.142697	0.002694
12	29	21.89421452	0.75	0.4	0.145201	0.002505
13	29	23.71873239	0.75	0.4	0.147545	0.002343
14	29	25.54325027	0.75	0.4	0.149748	0.002203
15	29	27.36776815	0.75	0.4	0.151828	0.002081
16	29	29.19228602	0.75	0.4	0.153801	0.001972
17	29	31.0168039	0.75	0.4	0.155677	0.001876

18	29	32.84132178	0.75	0.4	0.157467	0.00179
19	29	34.66583965	0.75	0.4	0.159179	0.001712
20	29	36.49035753	0.75	0.4	0.16082	0.001641
21	29	38.31487541	0.75	0.4	0.162397	0.001577
22	29	40.13939328	0.51	0.5	0.162574	0.000177
23	29	41.96391116	0.51	0.5	0.164391	0.001817
24	29	43.78842904	0.51	0.5	0.16615	0.001758
25	29	45.61294691	0.51	0.5	0.167854	0.001704
26	29	47.43746479	0.51	0.5	0.169508	0.001654
27	29	49.26198267	0.51	0.5	0.171115	0.001607
28	29	51.08650054	0.51	0.5	0.172678	0.001563
29	29	52.91101842	0.51	0.5	0.174199	0.001522
30	29	54.73553629	0.51	0.5	0.175682	0.001483
31	29	56.56005417	0.51	0.5	0.177128	0.001446
32	29	58.38457205	0.51	0.5	0.178539	0.001411
33	29	60.20908992	0.51	0.5	0.179918	0.001379
34	29	62.0336078	0.51	0.5	0.181266	0.001348
35	29	63.85812568	0.51	0.5	0.182584	0.001318
36	29	65.68264355	0.51	0.5	0.183875	0.00129
37	29	67.50716143	0.51	0.5	0.185139	0.001264
38	29	69.33167931	0.51	0.5	0.186377	0.001238
39	29	71.15619718	0.51	0.5	0.187591	0.001214
40	29	72.98071506	0.51	0.5	0.188782	0.001191
41	29	74.80523294	0.51	0.5	0.189951	0.001169
42	29	76.62975081	0.51	0.5	0.191099	0.001148
43	29	78.45426869	0.51	0.5	0.192227	0.001127
44	29	80.27878657	0.51	0.5	0.193335	0.001108
45	29	82.10330444	0.51	0.5	0.194424	0.001089
46	29	83.92782232	0.51	0.5	0.195495	0.001071
47	29	85.7523402	0.51	0.5	0.196549	0.001054
48	29	87.57685807	0.51	0.5	0.197586	0.001037
49	29	89.40137595	0.51	0.5	0.198608	0.001021
49.9	29	91.04344204	0.51	0.5	0.199513	0.000906
49.91	29	91.06168722	0.51	0.5	0.199523	9.99E-06
49.92	29	91.07993239	0.51	0.5	0.199533	9.99E-06
49.93	29	91.09817757	0.51	0.5	0.199543	9.99E-06
49.94	29	91.11642275	0.51	0.5	0.199553	9.99E-06
49.95	29	91.13466793	0.51	0.5	0.199563	9.99E-06
49.96	29	91.15291311	0.51	0.5	0.199573	9.99E-06
49.97	29	91.17115829	0.51	0.5	0.199583	9.99E-06
49.98	29	91.18940347	0.51	0.5	0.199593	9.98E-06
49.99	29	91.20764865	0.51	0.5	0.199603	9.98E-06
50	29	91.22589382	0.51	0.5	0.199613	9.98E-06

3.1.3 Graph Current vs velocity.



3.2 Constant temperature hot-film anemometer

(b) Constant temperature hot-film anemometer: The expected velocity measurement range is 1 m/s to 50 m/s. The accuracy of the velocity measurement must be 0.01 m/s. The maximum current allowed to go through the probe is 200 mA. The accuracy of the current measurement sensitivity is 10 μA. Take ambient temperature (Ta) as 27 degrees Celsius. The probe temperature (Ts) should be kept at a value between 1.5-2 times of the ambient temperature (Ts = [1.5-2] *Ta). It is recommended to keep the ratio of probe width (w) and probe thickness (t) as 1000 (w/t=1000). Therefore, you may assume the film as a flat plate.

(i) Suggest probe temperature and width

(ii) Provide Current vs velocity graph for the suggested design parameters

Resistivity of Platinum = 0.000000106Ωm [2]

(02) Constant temperature hot film anemometer,

* velocity range - 1 to $50\,ms^{-1}$
* Accuracy - $0.01\,ms^{-1}$, $10\,\mu A$
* T_a - 27^oC , T_s - $[1.5-2]\,T_a$
* ratio of Probe width/thick = 1000
* ~~assume~~

* assume film as flat plate,

For flat plate,

Laminar : $Nu = hL/k = 0.664\,Re^{0.5}\,Pr^{1/3}$

Turbulent : $0.037\,Re^{0.8}\,Pr^{1/3}$ $\quad 0.6 < Pr < 60$, $\quad 5\times10^5 < Re_L < 10^7$

Power dissipation,

$$P = I^2R$$

$$= I^2 \times \frac{\rho d}{tW}$$

$$= \frac{I^2\,\rho d}{W^2/1000} = \frac{I^2\,1000\,\rho d}{W^2}$$

$W = 1000t$

heat transfer through ~~heat~~ convection on wire,

* when $Re = 5 \times 10^5$
* $Re = \rho v J / \mu$ * width $= 0.16m$

$$Q = Ah\Delta T$$

$$= 2 \times 0.6664\, KU \left[\frac{\rho \cdot v \cdot D}{\mu}\right]^{0.5} \times (P_r)^{1/3} (T_s - T_a)$$

$$Q = P$$

$$2 \times 0.664 \times 10^{-3} \times K\alpha \left[\frac{\rho v D}{\mu}\right]^{0.5} \times P_r^{1/3} (T_s - T_a) = \frac{I^2 \beta 4}{w^2/1000}$$

$$I^2 = 2 \times 0.664 \times 10^{-3} \times K \times \frac{\rho^{0.5} \times D^{0.5}}{\mu^{0.5}} \times P_r^{1/3} (T_s - T_a) \times \frac{w^2}{\cancel{1000}\beta}$$

$$I^2 \propto v^{0.5}$$

$$I^2 = C_2 v^{0.5}$$

$$C_2 = \frac{2 \times 0.664 \times 10^{-3} \times k \rho^{0.5} \times w^{1/2} \times P_r^{1/3} \times (T_s - T_a)}{\beta \mu^{0.5}}$$

$$I^2 = C_2 v^{0.5}$$

$$2 I \Delta I = C_2 \times 0.5 \times v^{-0.5} \times \Delta v$$

$$\frac{\Delta I}{\Delta v} = \frac{C_2^{0.5}}{4 v^{0.75}}$$

Res

Current sensitivity 10 μA, robust accuracy 0.01 ms^{-1}

$$\Delta I / \Delta r \geq 10^{-3} A (ms^{-1})^{-1}$$

Min value $= 10^{-3}$

$$\frac{C_2^{1/2}}{4 v^{3/4}} \geq 10^{-3}$$

$$C_2 \geq 5.65685 \times 10^{-3}$$

* when C_2 is 5.65685 and I_{max} 200 μA

$W = 0.45$ mm

$T_s = 46^\circ C$

3.2.1 Data and Parameters

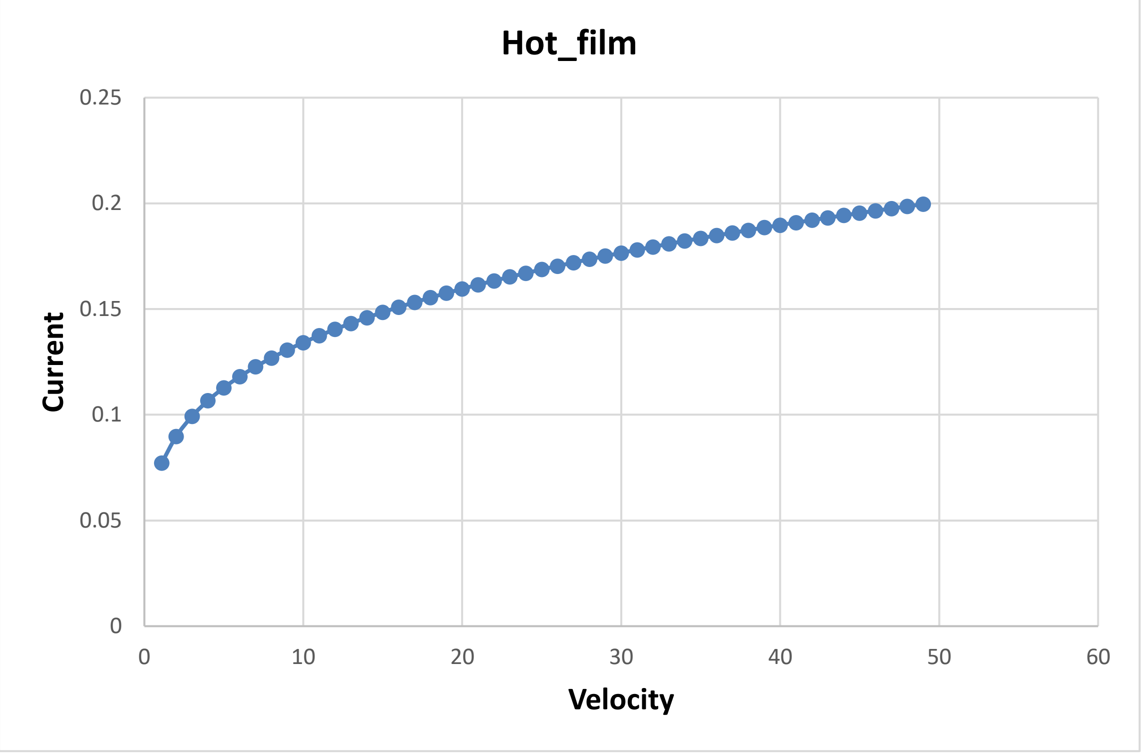
Prs =	0.70448	(assumption)
Pr =	0.707	
n=	0.36	for all Pr<10
Ts =	45	
Ta =	27	
K =	0.0263	
μ =	0.00001846	
ρ =	1.1614	
π =	3.14159265	
Prs	0.707	
W(mm)	0.45	

3.2.2 Calculation

U (m/s)	w	Re	I	dI
1	0.00045	28.3114843	0.075451	
1.01	0.00045	28.5945991	0.075639	0.000188
1.02	0.00045	28.877714	0.075826	0.000187
1.03	0.00045	29.1608288	0.076011	0.000185
1.04	0.00045	29.4439437	0.076195	0.000184
1.05	0.00045	29.7270585	0.076377	0.000183
1.06	0.00045	30.0101733	0.076558	0.000181
1.07	0.00045	30.2932882	0.076738	0.00018
1.08	0.00045	30.576403	0.076917	0.000179
1.09	0.00045	30.8595179	0.077094	0.000177
1.1	0.00045	31.1426327	0.077271	0.000176
2	0.00045	56.6229686	0.089727	0.012457
3	0.00045	84.9344529	0.099299	0.009572
4	0.00045	113.245937	0.106704	0.007405
5	0.00045	141.557421	0.112826	0.006122
6	0.00045	169.868906	0.118088	0.005262
7	0.00045	198.18039	0.122727	0.00464
8	0.00045	226.491874	0.126893	0.004166
9	0.00045	254.803359	0.130685	0.003792
10	0.00045	283.114843	0.134173	0.003488
11	0.00045	311.426327	0.137409	0.003235
12	0.00045	339.737811	0.140431	0.003022
13	0.00045	368.049296	0.143269	0.002838
14	0.00045	396.36078	0.145948	0.002679
15	0.00045	424.672264	0.148487	0.002539
16	0.00045	452.983749	0.150903	0.002415
17	0.00045	481.295233	0.153207	0.002305
18	0.00045	509.606717	0.155412	0.002205
19	0.00045	537.918202	0.157527	0.002115

20	0.00045	566.229686	0.15956	0.002033
21	0.00045	594.54117	0.161518	0.001958
22	0.00045	622.852654	0.163408	0.001889
23	0.00045	651.164139	0.165234	0.001826
24	0.00045	679.475623	0.167001	0.001767
25	0.00045	707.787107	0.168714	0.001713
26	0.00045	736.098592	0.170377	0.001662
27	0.00045	764.410076	0.171992	0.001615
28	0.00045	792.72156	0.173563	0.001571
29	0.00045	821.033044	0.175092	0.001529
30	0.00045	849.344529	0.176582	0.00149
31	0.00045	877.656013	0.178036	0.001453
32	0.00045	905.967497	0.179454	0.001419
33	0.00045	934.278982	0.18084	0.001386
34	0.00045	962.590466	0.182195	0.001355
35	0.00045	990.90195	0.18352	0.001325
36	0.00045	1019.21343	0.184817	0.001297
37	0.00045	1047.52492	0.186087	0.00127
38	0.00045	1075.8364	0.187332	0.001245
39	0.00045	1104.14789	0.188553	0.00122
40	0.00045	1132.45937	0.18975	0.001197
41	0.00045	1160.77086	0.190925	0.001175
42	0.00045	1189.08234	0.192079	0.001154
43	0.00045	1217.39382	0.193212	0.001133
44	0.00045	1245.70531	0.194326	0.001114
45	0.00045	1274.01679	0.19542	0.001095
46	0.00045	1302.32828	0.196497	0.001077
47	0.00045	1330.63976	0.197556	0.001059
48	0.00045	1358.95125	0.198599	0.001043
49	0.00045	1387.26273	0.199625	0.001026
49.9	0.00045	1412.74307	0.200536	0.00091
49.91	0.00045	1413.02618	0.200546	1E-05
49.92	0.00045	1413.3093	0.200556	1E-05
49.93	0.00045	1413.59241	0.200566	1E-05
49.94	0.00045	1413.87553	0.200576	1E-05
49.95	0.00045	1414.15864	0.200586	1E-05
49.96	0.00045	1414.44176	0.200596	1E-05
49.97	0.00045	1414.72487	0.200606	1E-05
49.98	0.00045	1415.00798	0.200616	1E-05
49.99	0.00045	1415.2911	0.200626	1E-05
50	0.00045	1415.57421	0.200636	1E-05

3.2.3 Graph Current vs velocity.



4 References

[1] L. H. a. M. Dunckel, Hot Wire and Hot Film.

[2] D. C. Giancoli, Physics, 1995.