Nusselt Correlations for Select Substation Bus

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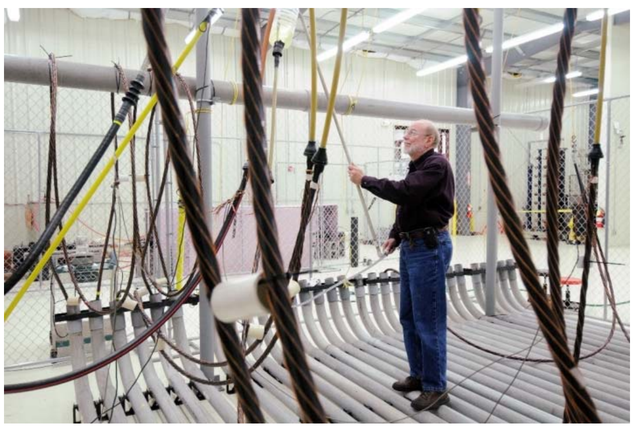
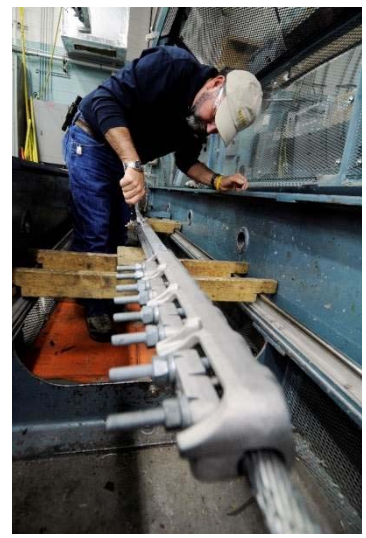
Power & Energy Society®

NEETRAC Overview

- Non-profit, 37 member industry consortium at Georgia Tech
  - 37 Members – Utilities and Manufacturers
  - Represent ~65% of US + Canadian electric customers
- Provide third-party testing and application research services.



Electrical Section



Mechanical Section

NEETRAC Overview

Agenda

1. Project Overview & Refresher
2. Forced Convection Correlations
3. Natural Convection Correlations
4. Effect on Calculated Ampacity
5. Discussion / Questions

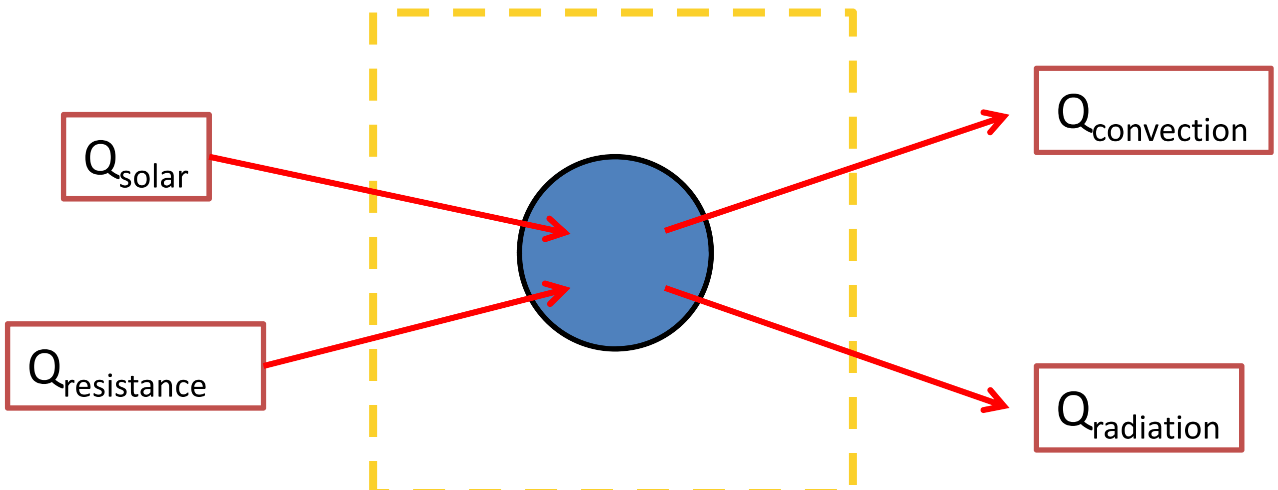
Project Overview & Refresher

- Developed Nusselt correlations to improve bus ampacity and temperature prediction accuracy.
  - Forced Convection
  - Natural (Free) Convection
- Rectangular, UAB, IWBC
  - Multiple orientations

Project Overview & Refresher

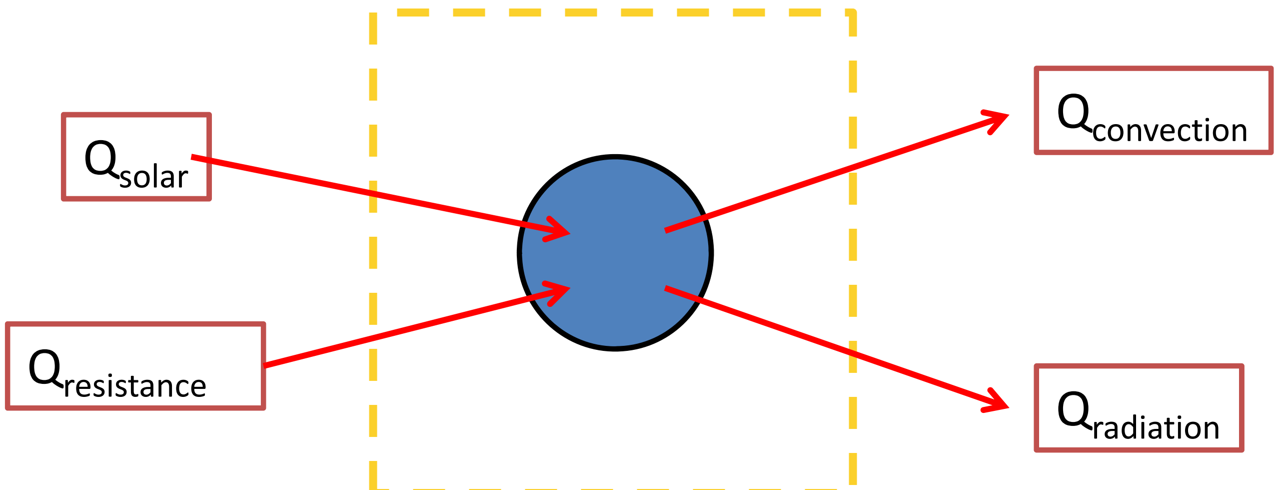
I^2RF

$$Q_{resistance} + Q_{sun} = Q_{convection} + Q_{radiation}$$

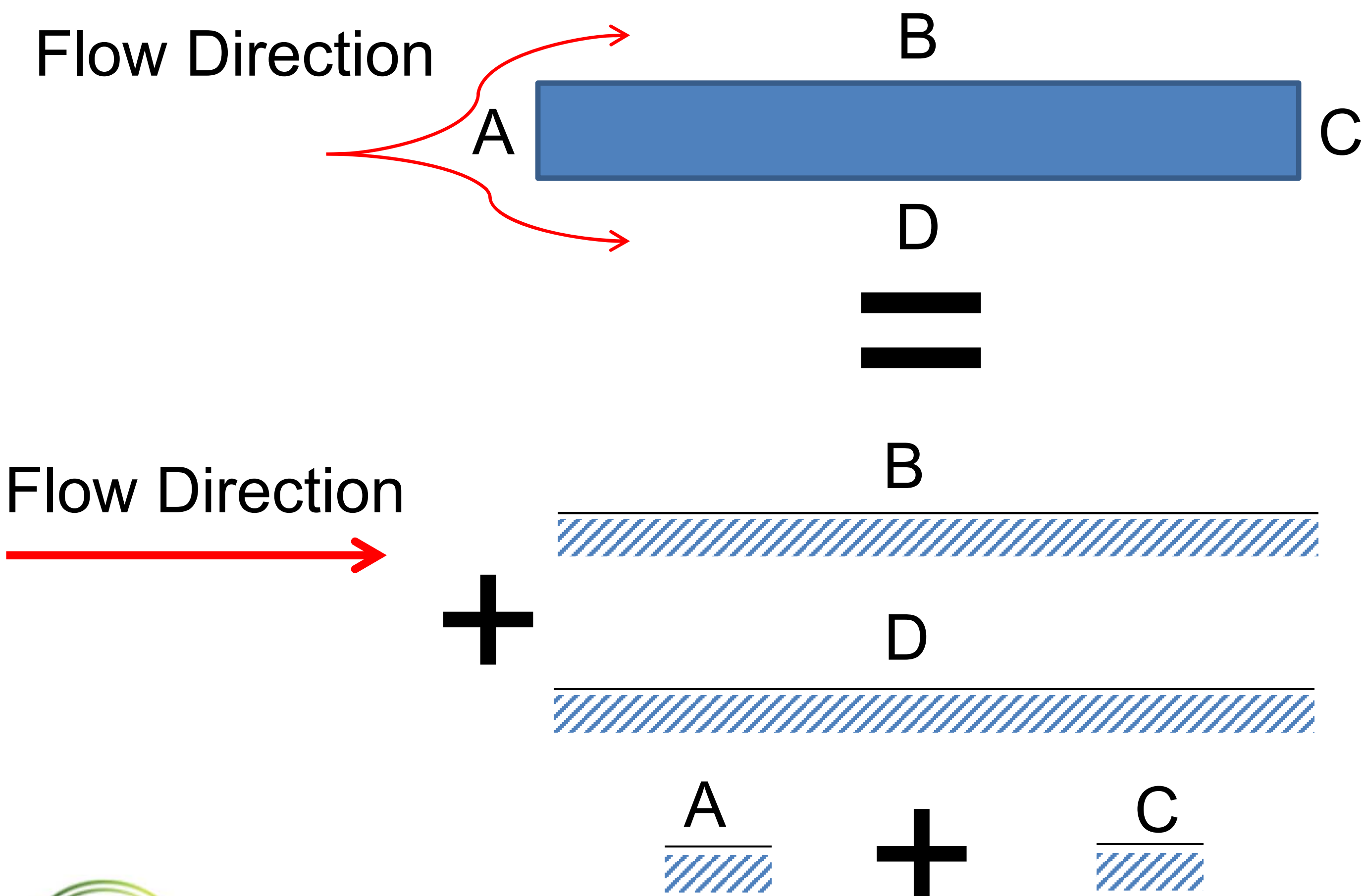


Project Overview & Refresher

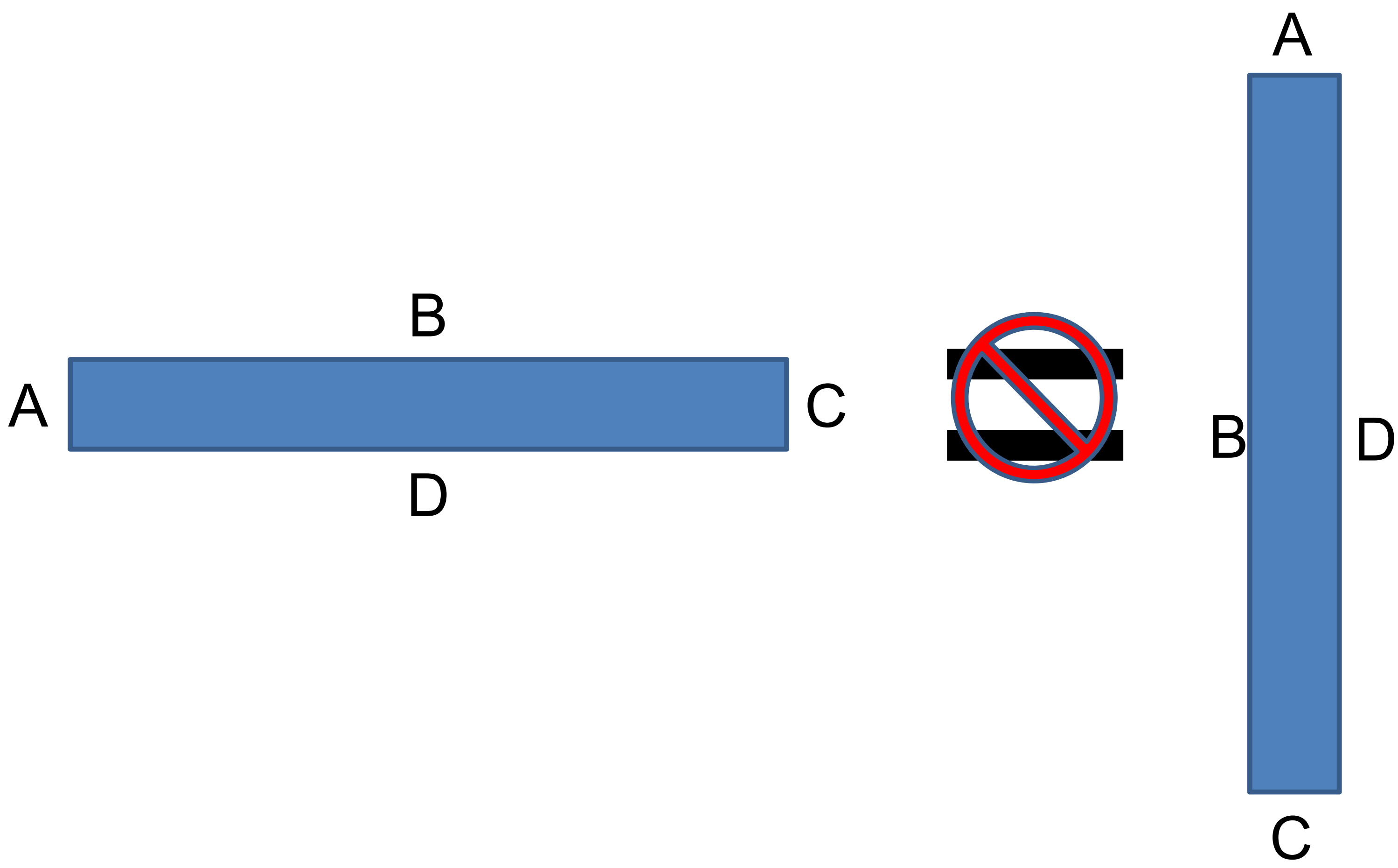
$$I = \sqrt{\frac{Q_{conv} + Q_{rad} - Q_{solar}}{RF}}$$



Project Overview & Refresher

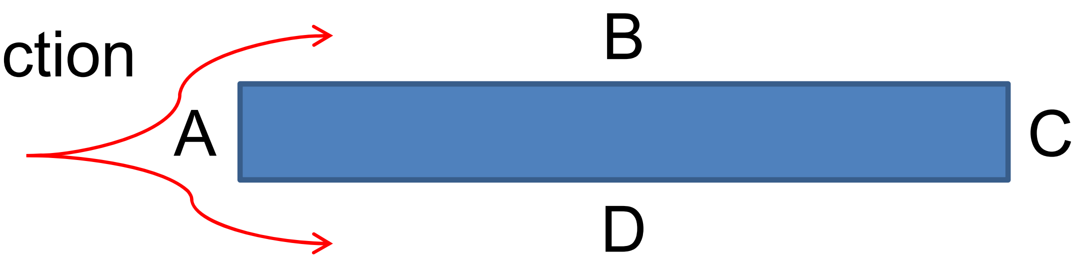


Project Overview & Refresher



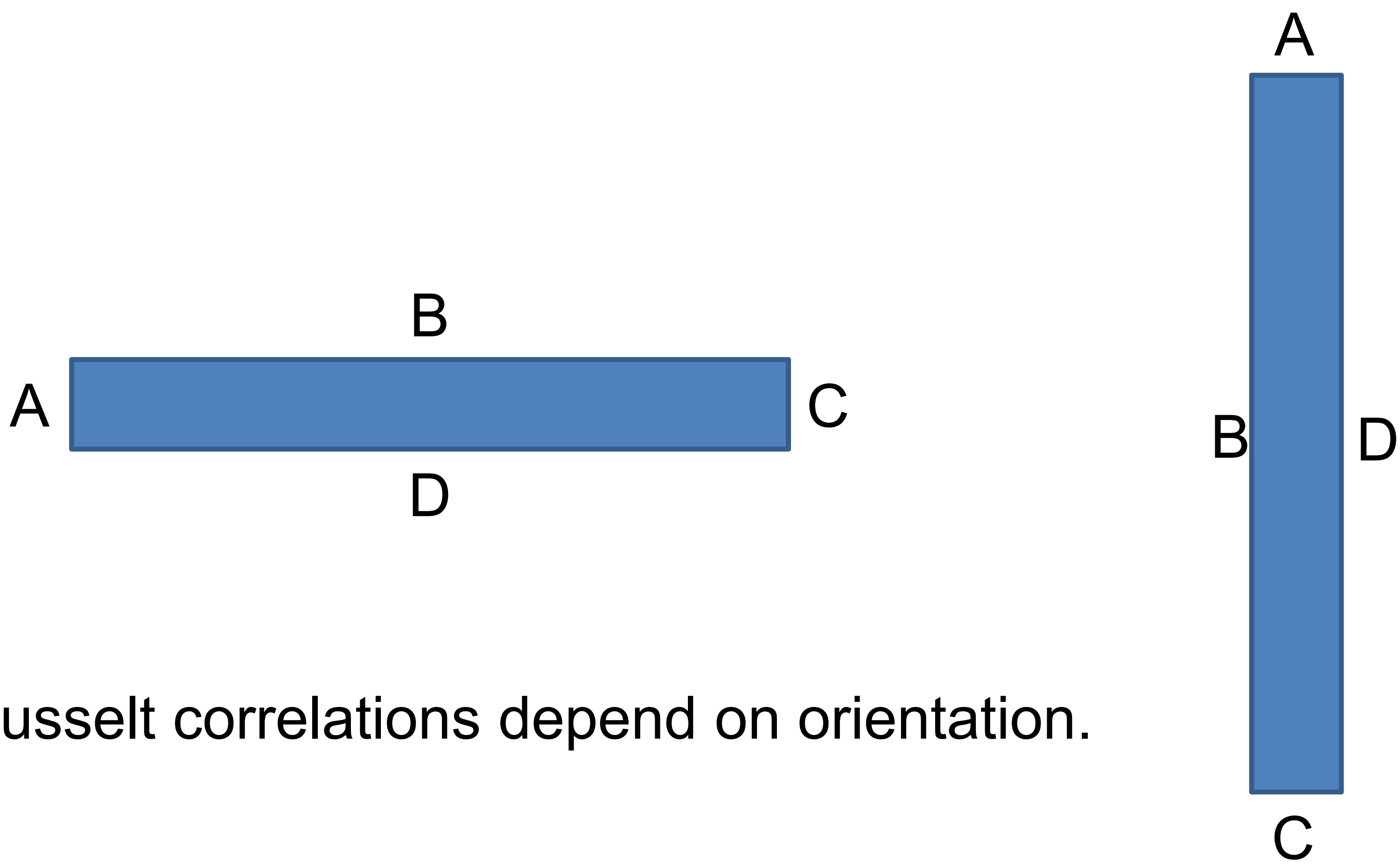
Project Overview & Refresher

Flow Direction



Nusselt correlations calculate the convective heat transfer without splitting the bus into planes.

Project Overview & Refresher



Nusselt correlations depend on orientation.

Project Overview & Refresher

- The current IEEE 605 method deconstructs a bus geometry into flat plates. The convective cooling of each plate is calculated separately and summed.
  - This method is orientation independent.
- Nusselt correlations are for the whole body and are orientation dependent.

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3. Natural Convection Correlations
4. Effect on Calculated Ampacity
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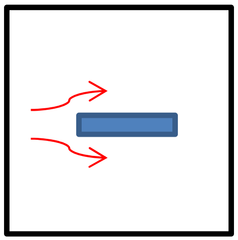
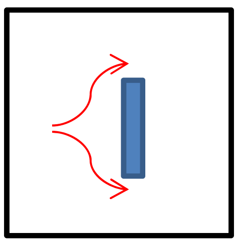
Forced Convection Correlations

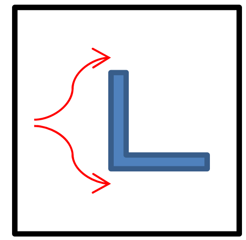
Forced Convection Correlations



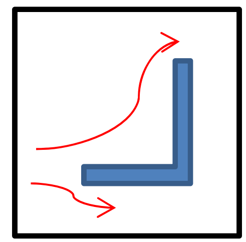
Horizontal Rectangular



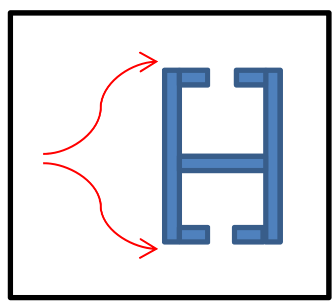
Vertical Rectangular



UAB Closed



UAB Open

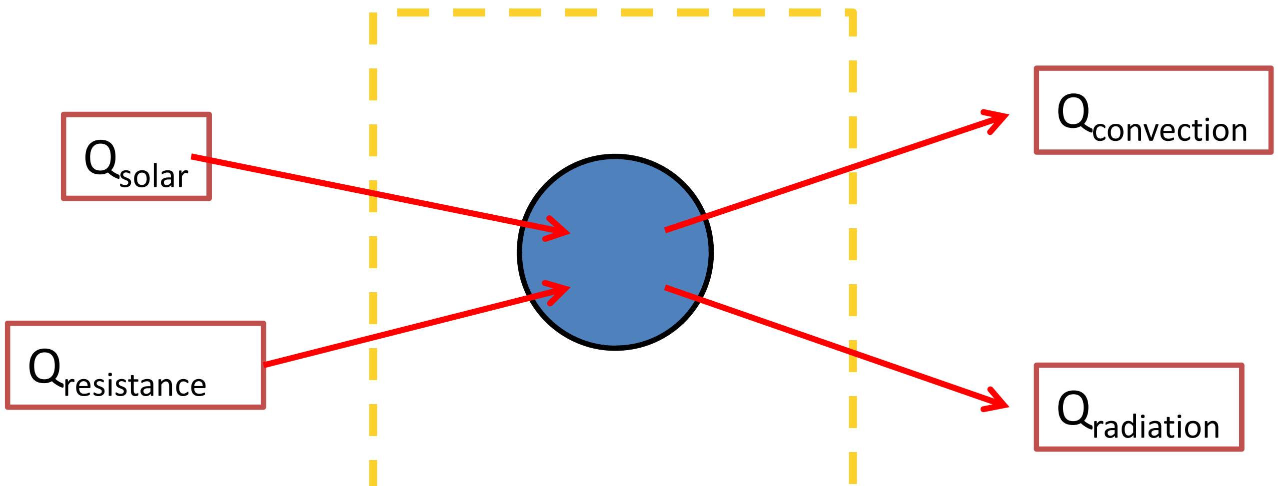


IWBC

Forced Convection Correlations

$hA\Delta T$ How is *h* determined?

$$I = \sqrt{\frac{Q_{conv} + Q_{rad} - Q_{solar}}{RF}}$$



Forced Convection Correlations

Experiments have shown a relationship between the Nusselt, Reynolds, and Prandtl numbers to find *h*.

$$Nu = \frac{hL}{k} = C(Re^{m})Pr^{0.33}$$

Prandtl – Typically taken as 0.7 for air

$$Re = \frac{VL}{\nu}$$

Fluid Velocity

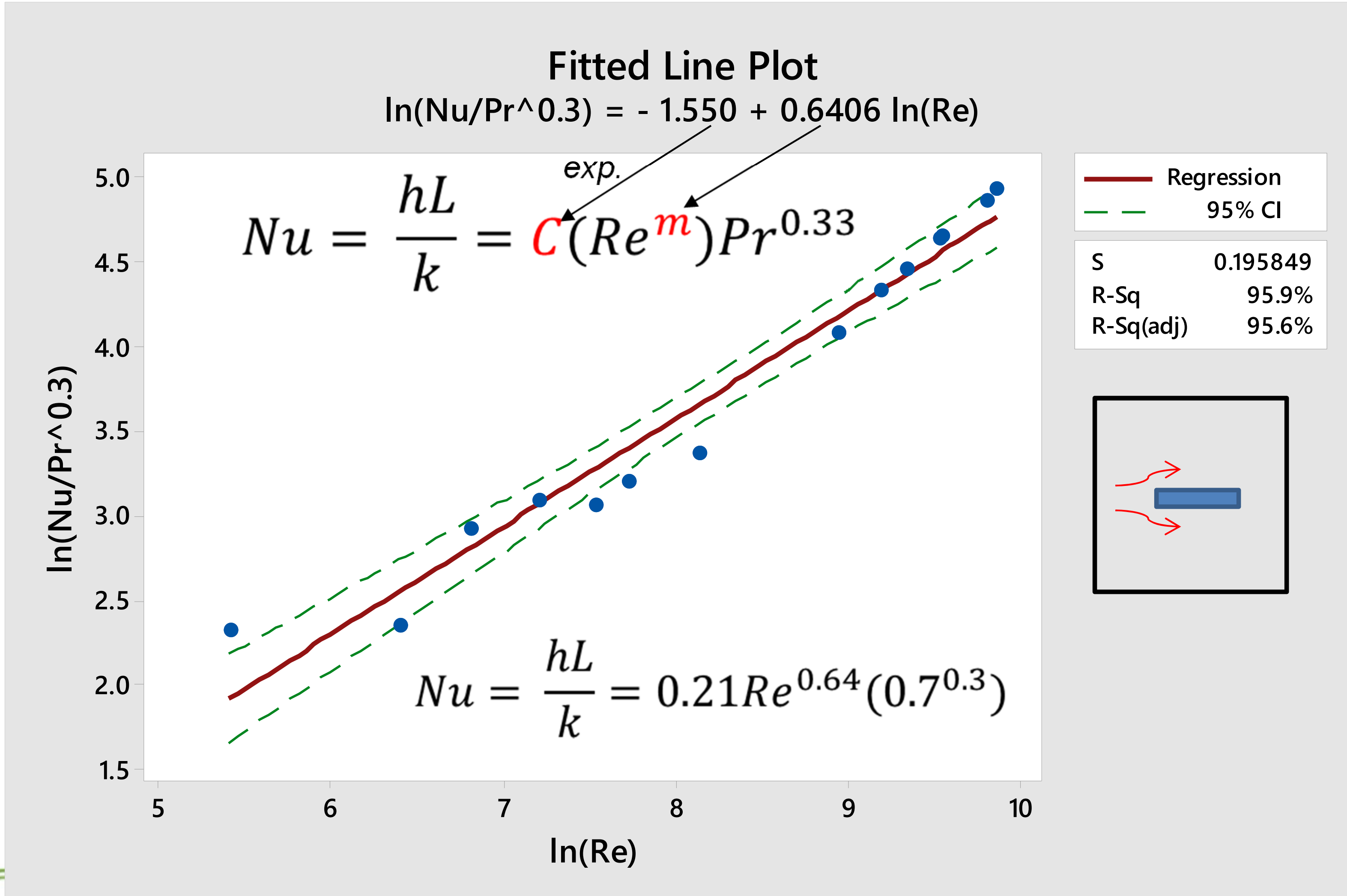
Characteristic Length

Kinematic Viscosity

Forced Convection Correlations

- Wind tunnel experiments measured *h*.
- The heat transfer coefficient was calculated from:
  - Bus and ambient temperature
  - Bus dimensions and emissivity measurments
  - Wind speed
  - Current and resistance readings
- Nusselt and Reynolds were calculated from the data.

Forced Convection Correlations



Forced Convection Correlations

Geometry	Correlation	Reynold's Range
Horizontal Rectangular	$Nu = 0.21Re^{0.64}(0.7^{0.3})$	250 < Re < 19,000
Vertical Rectangular	$Nu = 0.30Re^{0.63}(0.7^{0.3})$	500 < Re < 22,000
UAB Closed	$Nu = 0.072Re^{0.75}(0.7^{0.3})$	2,500 < Re < 13,000
UAB Open	$Nu = 0.085Re^{0.70}(0.7^{0.3})$	2,800 < Re < 13,000
IWBC	$Nu = 0.038Re^{0.76}(0.7^{0.3})$	1,000 < Re < 27,500

Forced Convection Correlations

Buses operate in a narrow temperature range. Air properties are relatively stable in this range. By assuming constant properties, the formulas are simplified.

$$Nu = \frac{hL}{k} = 0.21(VL/\nu)^{0.64}(0.7)^{0.33}$$

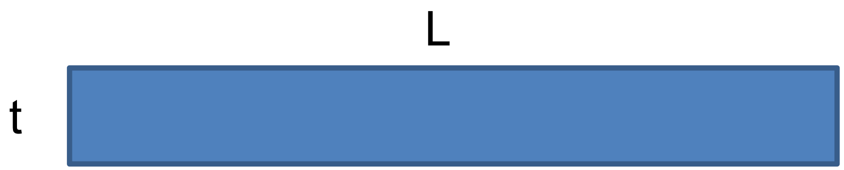
$$h = \frac{k}{L}(0.21(VL)^{0.64}\,(1/\nu)^{0.64}\,(0.7)^{0.33}) \quad \nu = 18.9 * \frac{10^{-6}m^2}{s},$$

$$\mathrm{k} = 0.0288\ \mathrm{W/(m°C)}$$

$$h = 5.67\frac{V^{0.64}}{L^{0.36}}$$

$$Q_{conv} = hA\Delta T = \left(5.67\frac{V^{0.64}}{L^{0.36}}\right)A\Delta T$$

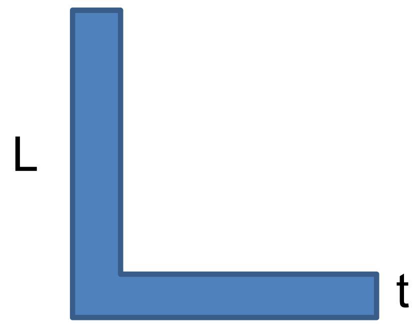
Forced Convection Correlations



$$A_s = (2L + 2t)(1\ [m])$$

$$Q_{conv} = hA\Delta T = \left(5.67\frac{V^{0.64}}{L^{0.36}}\right)2(L + t)\Delta T = \left(11.34\frac{V^{0.64}}{L^{0.36}}\right)(L + t)\Delta T$$

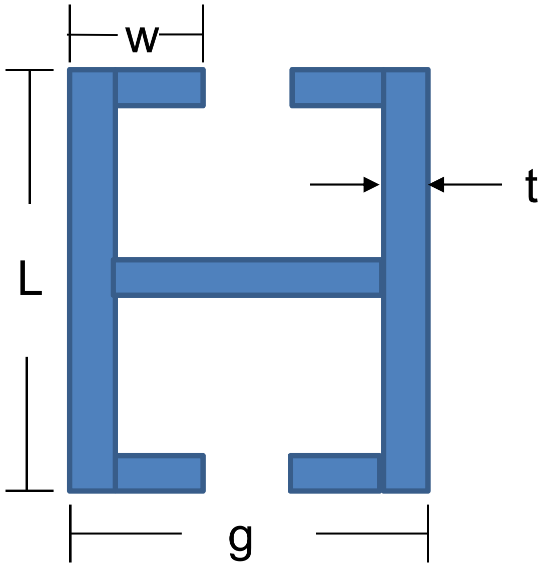
Forced Convection Correlations



$$A_s = (2L + 2t + 2(L - t))(1\ [m]) = 4L$$

$$Q_{conv} = hA\Delta T = \left(6.50\frac{V^{0.75}}{L^{0.25}}\right)4L\Delta T = \left(26.0\frac{V^{0.75}}{L^{0.25}}\right)L\Delta T$$

Forced Convection Correlations



$$A_s = 4L + 2g + 8w - 10t$$

$$Q_{conv} = hA\Delta T = \left(3.78\frac{V^{0.76}}{L^{0.24}}\right)(4L + 2g + 8w - 10t)$$
$$= \left(7.56\,\frac{V^{0.76}}{L^{0.24}}\right)(2L + g + 4w - 5t)\Delta T$$

Forced Convection Correlations

Geometry	Summation of convective losses
Horizontal Rectangular	$Q_{conv} = \left(11.34\frac{V^{0.64}}{L^{0.36}}\right)(L+t)\Delta T$
Vertical Rectangular	$Q_{conv} = \left(14.69\frac{V^{0.63}}{L^{0.37}}\right)(L+t)\Delta T$
UAB Closed	$Q_{conv} = \left(26.0\frac{V^{0.75}}{L^{0.25}}\right)L\Delta T$
UAB Open	$Q_{conv} = \left(17.82\frac{V^{0.70}}{L^{0.30}}\right)L\Delta T$
IWBC	$Q_{conv} = \left(7.56\frac{V^{0.76}}{L^{0.24}}\right)(2L+g+4w-5t)\Delta T$

Forced Convection Correlations

Geometry	Summation of convective losses
Horizontal Rectangular	$Q_{conv} = (8.265/L^{0.36})(L + t)\Delta T$
Vertical Rectangular	$Q_{conv} = (10.760/L^{0.37})(L + t)\Delta T$
UAB Closed	$Q_{conv} = (17.946/L^{0.25})L\Delta T$
UAB Open	$Q_{conv} = (12.608/L^{0.30})L\Delta T$
IWBC	$Q_{conv} = (5.13/L^{0.24})(2L + g + 4w - 5t)\Delta T$

With 2 ft/s (0.61 m/s) assumption.

Agenda

1. Project Overview & Refresher
2. Forced Convection Correlations
3. **Natural Convection Correlations**
4. Effect on Calculated Ampacity
5. Discussion / Questions

Natural Convection Correlations

- Natural (Free) convection occurs when wind velocity is zero.
  - Outdoor bus in stagnant air
  - Indoor bus
- Natural convection depends on changes in air properties.

Natural Convection Correlations

- Similar to forced convection, Nusselt correlations calculate convective heat loss.

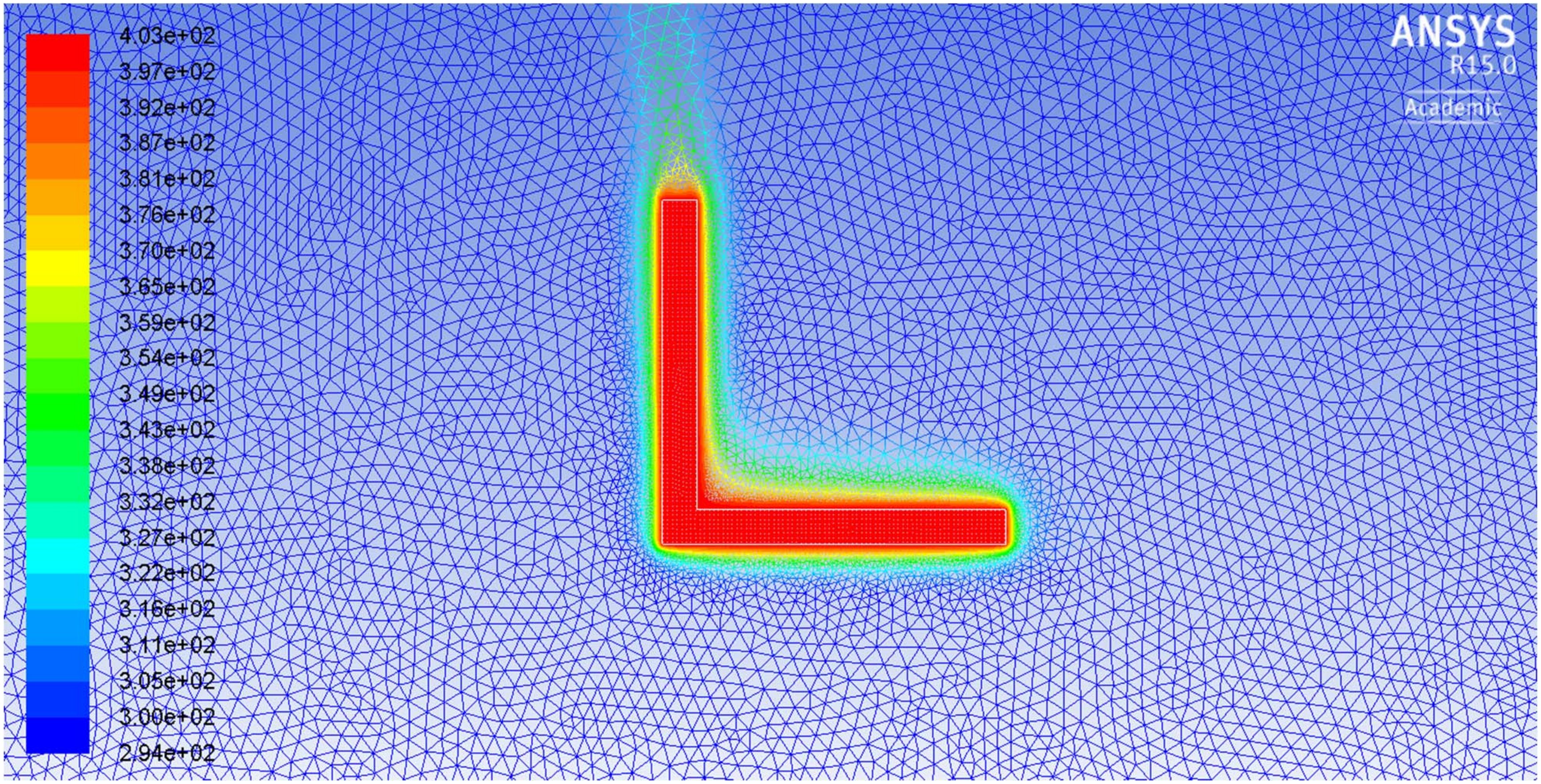
$$Nu = \frac{hL}{k} = C(Ra)^m$$

- These correlations use Rayleigh's number.

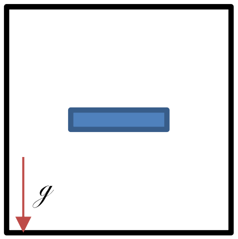
$$Ra = \frac{C_p \rho^2 g \beta \Delta T L^3}{\mu k}, \beta = \frac{1}{T_{film}}$$

Natural Convection Correlations

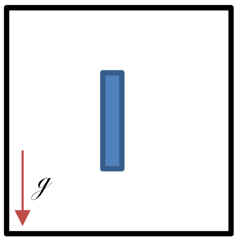
Natural Convection Correlations



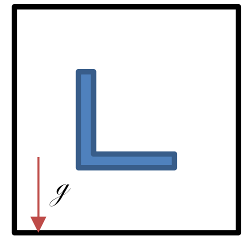
Natural Convection Correlations



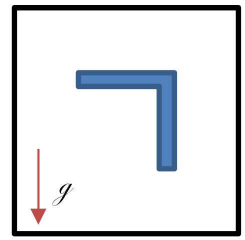
Horizontal Rectangular



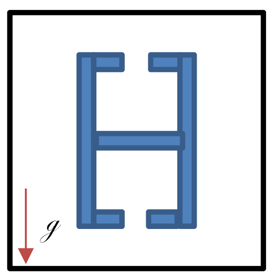
Vertical Rectangular



UAB "Up"



UAB "Down"



IWBC

Natural Convection Correlations

Geometry	Correlation	Reynold's Range
Horizontal Rectangular	$Nu = 1.81Ra^{0.20}$	25 < Ra < 8.5x10^5
Vertical Rectangular	$Nu = 1.69Ra^{0.26}$	25 < Ra < 8.5x10^5
UAB Up	$Nu = 1.44Ra^{0.25}$	7.1x10^3 < Ra < 5.9x10^4
UAB Down	$Nu = 1.35Ra^{0.26}$	7.2x10^3 < Ra < 6.3x10^4
IWBC	$Nu = 1.00Ra^{0.23}$	1.6x10^3 < Ra < 8.4x10^5

Natural Convection Correlations

- Unlike forced convection, natural convection requires changes in air properties.
- It is best to interpolate air properties from a data table.

Natural Convection Correlations

Geometry	Summation of convective losses
Horizontal Rectangular	$Q_{conv} = 3.62Ra^{0.20}(\frac{k}{L})(L+t)\Delta T$
Vertical Rectangular	$Q_{conv} = 3.38Ra^{0.26}(\frac{k}{L})(L+t)\Delta T$
UAB Up	$Q_{conv} = 5.76Ra^{0.25}k\Delta T$
UAB Down	$Q_{conv} = 5.40Ra^{0.26}k\Delta T$
IWBC	$Q_{conv} = 2.00Ra^{0.23}(\frac{k}{L})(2L+g+4w-5t)\Delta T$

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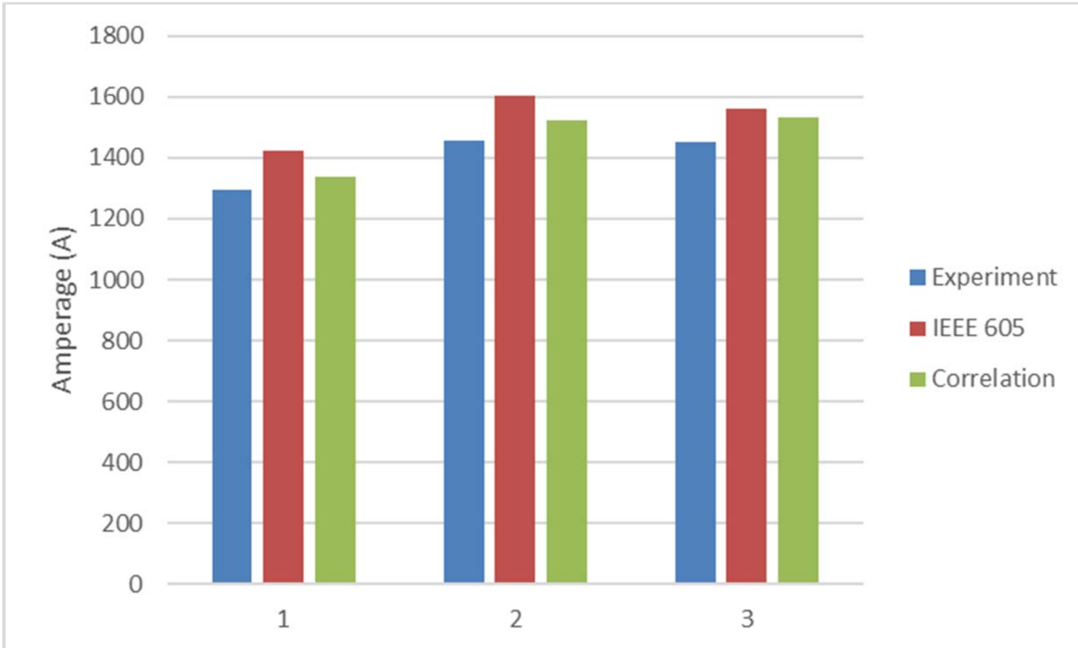
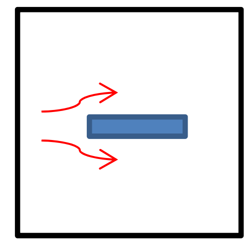
Effect on Ampacity

- The following graphs and tables use experimental data to compare the current 605 method and correlations.
  - Equation C.4 was used for forced convection.
  - Equations C.9 and C.10 were used for natural convection.
- The convection calculation method varied.
- Radiation was normalized across the methods, measured resistance was used, and skin effect was ignored (DC supply used in experiments).

Forced Convection

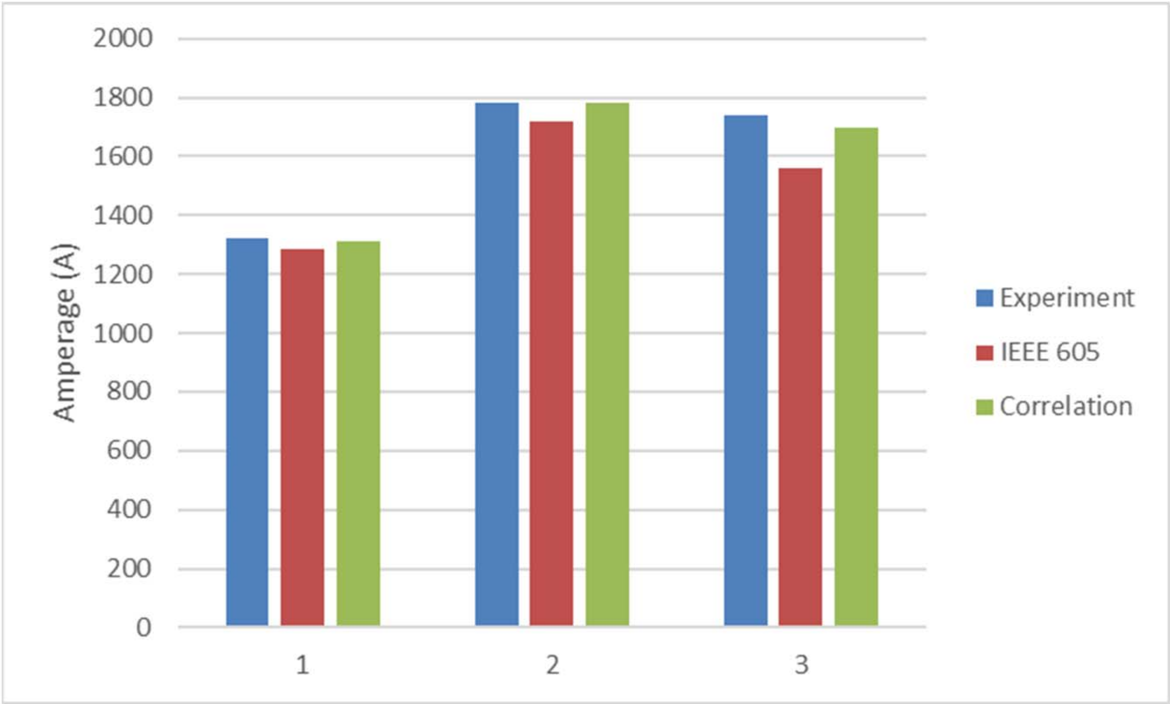
Effect on Ampacity

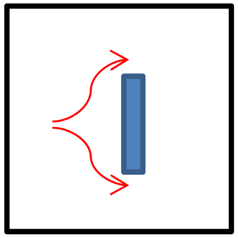




Case	Temp Rise	Velocity (m/s)	Experimental Current	IEEE 605 Current	605 – Exp. Error	New Method Current	New – Exp. Error
1	80	0.65	1295	1425	+10.0%	1338	+3.3%
2	90	0.96	1456	1604	+10.2%	1523	+4.6%
3	67	1.98	1452	1560	+7.4%	1530	+5.4%

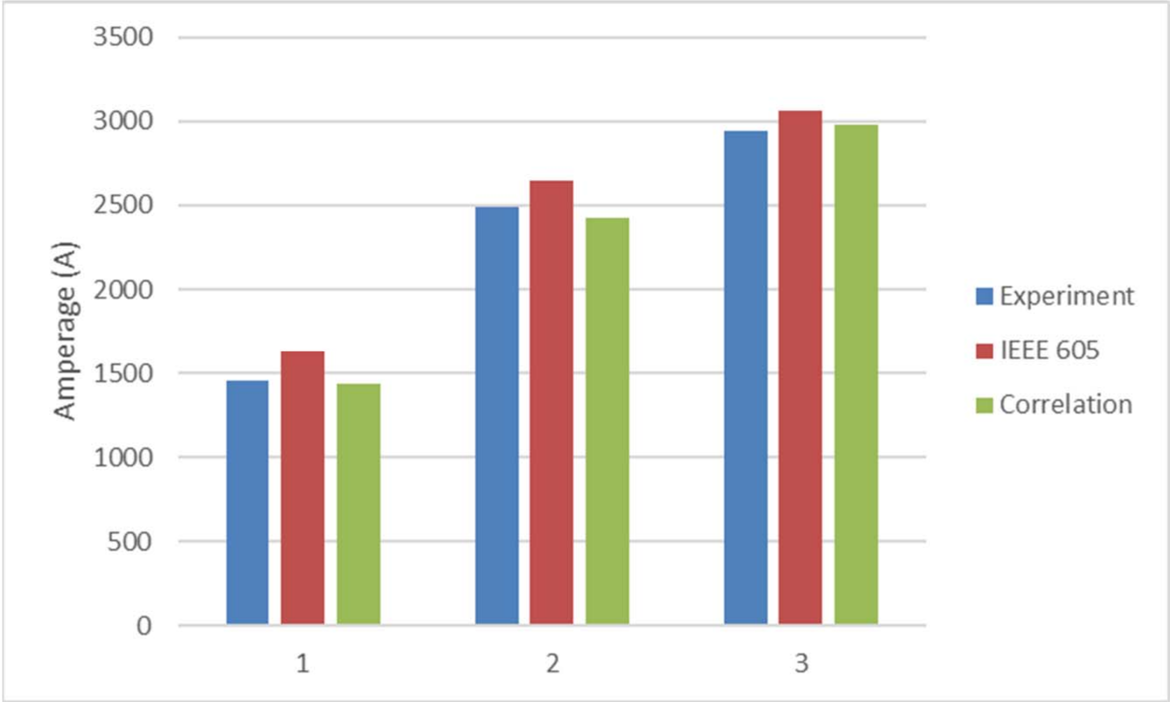
Effect on Ampacity

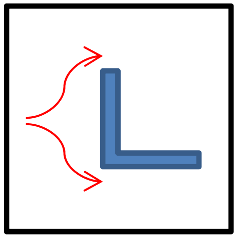




Case	Temp Rise	Velocity (m/s)	Experimental Current	IEEE 605 Current	605 – Exp. Error	New Method Current	New – Exp. Error
1	64	0.64	1323	1286	-2.8%	1314	-0.68%
2	99	0.98	1784	1716	-3.8%	1782	-0.11%
3	66	2.01	1741	1560	-10.4%	1697	-2.5%

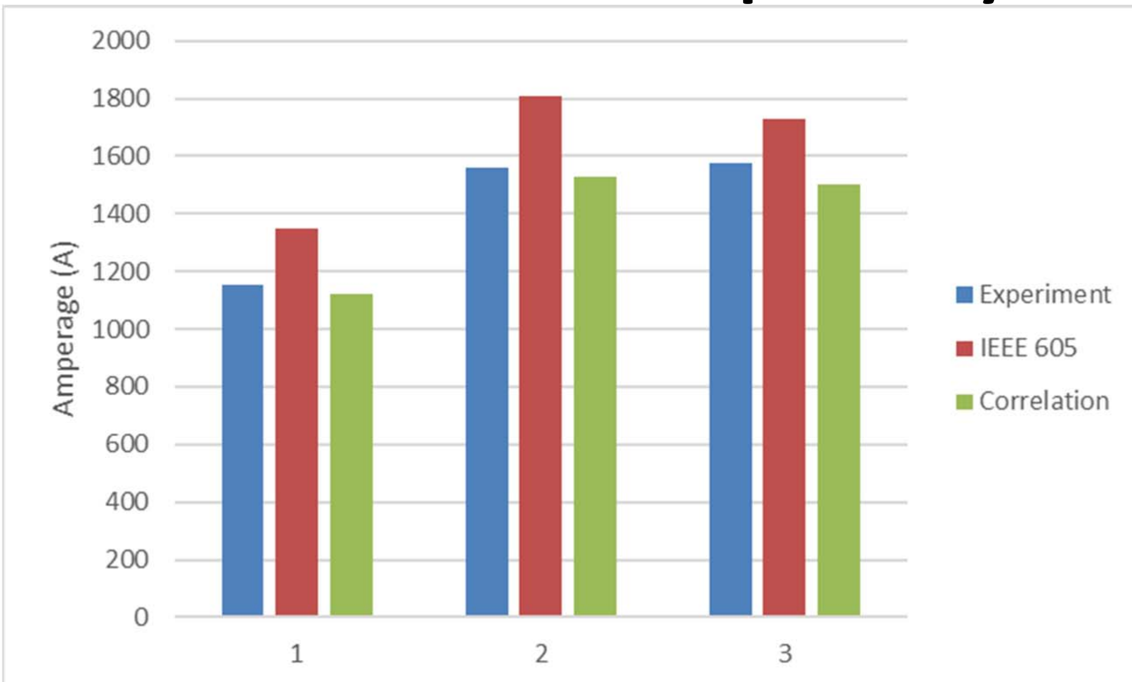
Effect on Ampacity

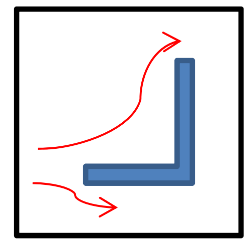




Case	Temp Rise	Velocity (m/s)	Experimental Current	IEEE 605 Current	605 – Exp. Error	New Method Current	New – Exp. Error
1	95	0.51	1459	1631	+11.8%	1436	-1.6%
2	45	0.92	2488	2646	+6.4%	2424	-2.6%
3	45	1.95	2944	3065	+4.1%	2979	+1.2%

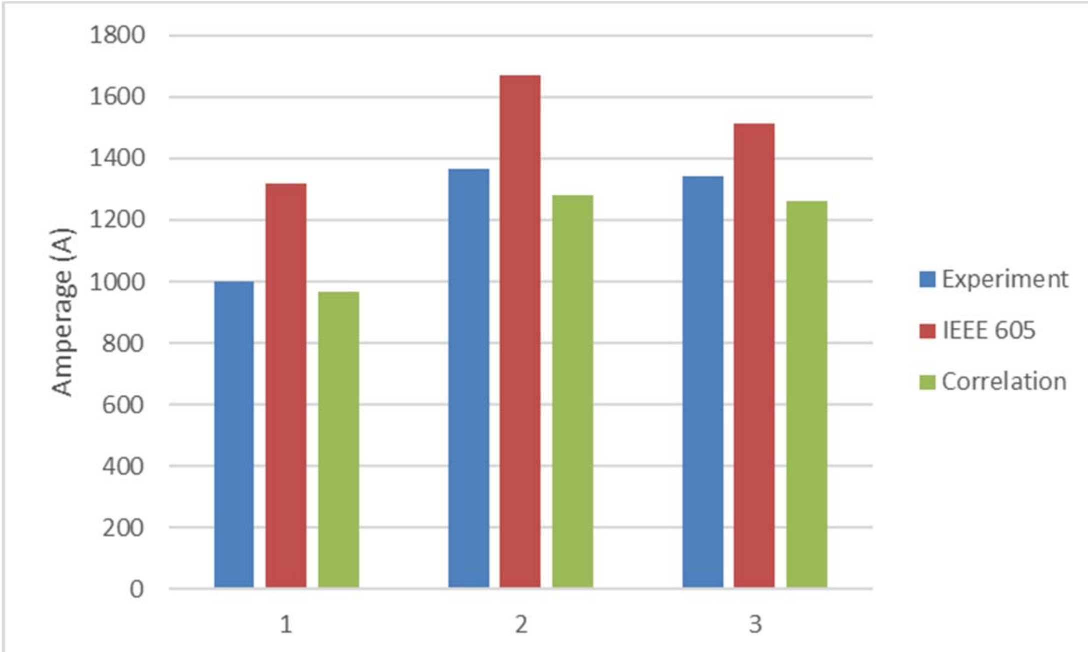
Effect on Ampacity

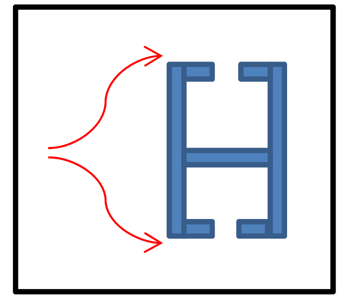




Case	Temp Rise	Velocity (m/s)	Experimental Current	IEEE 605 Current	605 – Exp. Error	New Method Current	New – Exp. Error
1	65	0.54	1153	1351	+17.2%	1123	-2.6%
2	95	1	1558	1808	+16.0%	1530	-1.8%
3	66	2.01	1576	1727	+9.6%	1501	-4.8%

Effect on Ampacity

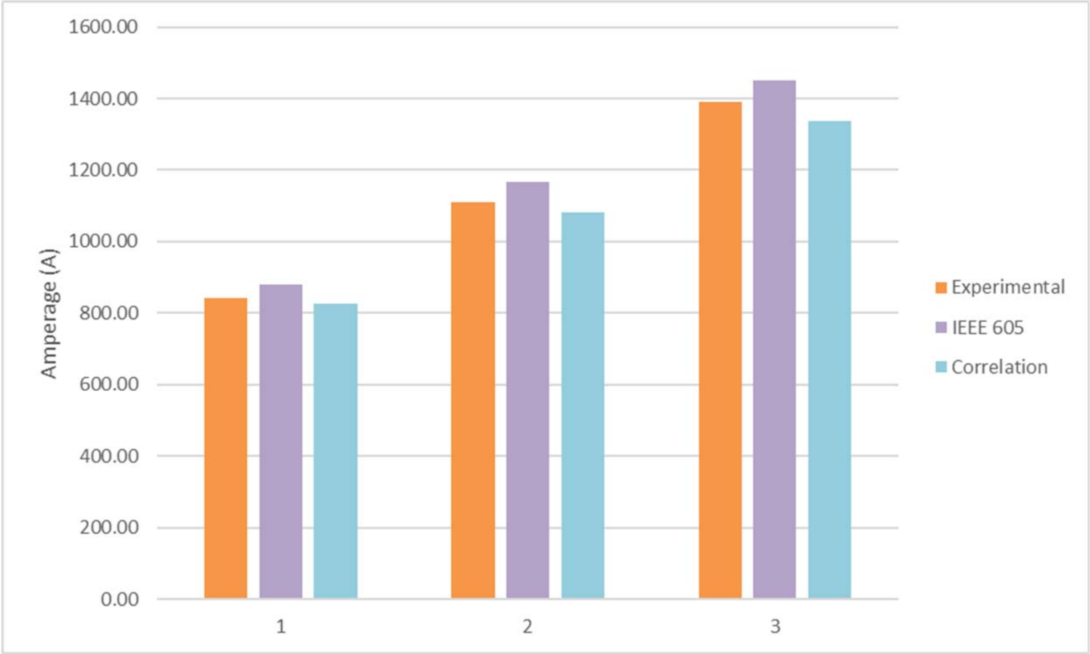


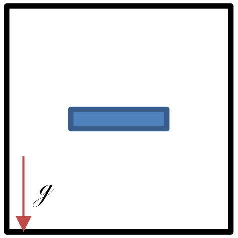


Case	Temp Rise	Velocity (m/s)	Experimental Current	IEEE 605 Current	605 – Exp. Error	New Method Current	New – Exp. Error
1	66	0.59	1001	1320	+31.9%	958	-4.3%
2	92	1.02	1367	1671	+22.2%	1279	-6.4%
3	61	2	1341	1514	+12.9%	1271	-5.2%

Natural Convection

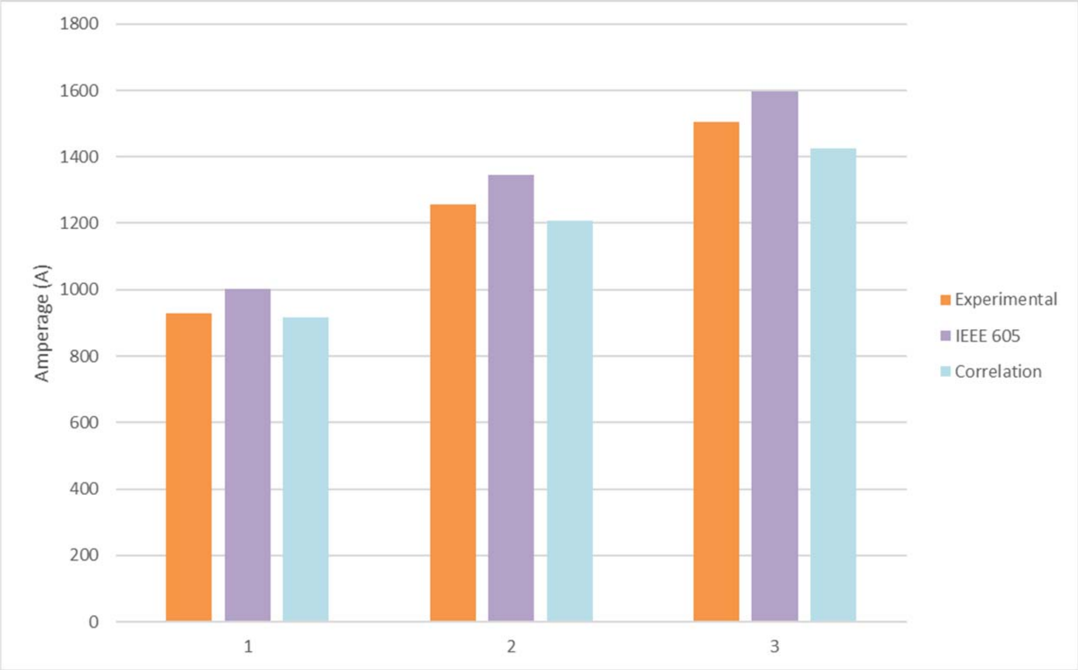
Effect on Ampacity

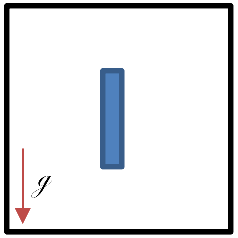




Case	Temp Rise	Experimental Current	IEEE 605 Current	605 – Exp. Error	New Method Current	New – Exp. Error
1	48	843	881	+4.5%	827	-1.9%
2	78	1110	1167	+5.2%	1082	-2.5%
3	111	1389	1451	+4.4%	1337	-3.8%

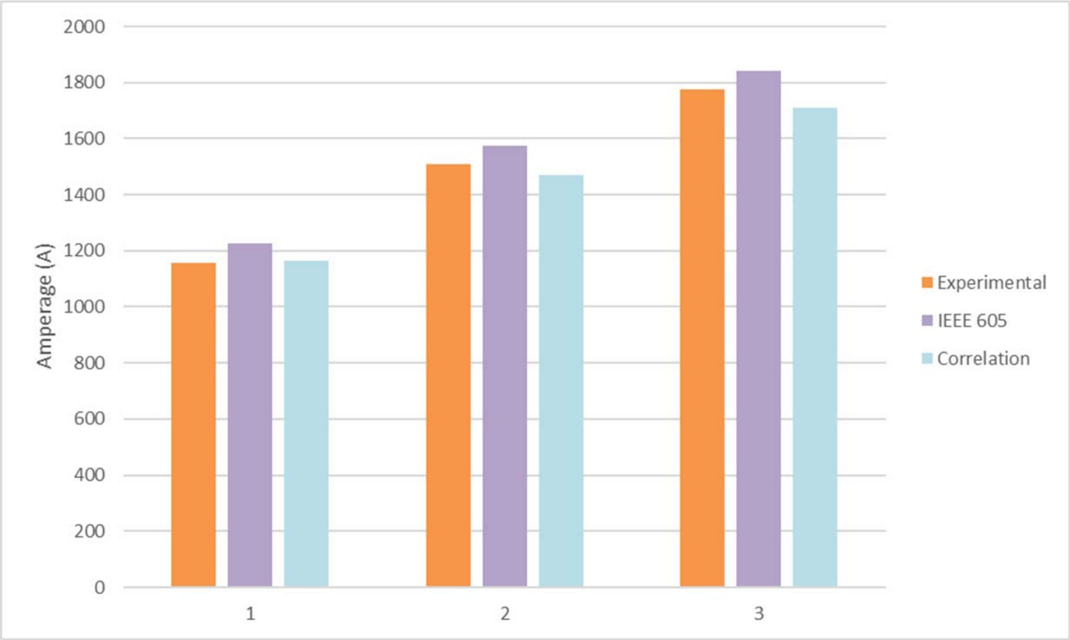
Effect on Ampacity

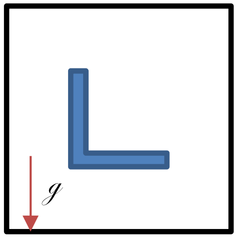




Case	Temp Rise	Experimental Current	IEEE 605 Current	605 – Exp. Error	New Method Current	New – Exp. Error
1	47	928	1001	+7.9%	914	-1.5%
2	79	1258	1344	+6.8%	1206	-4.1%
3	107	1505	1598	+6.2%	1422	-5.5%

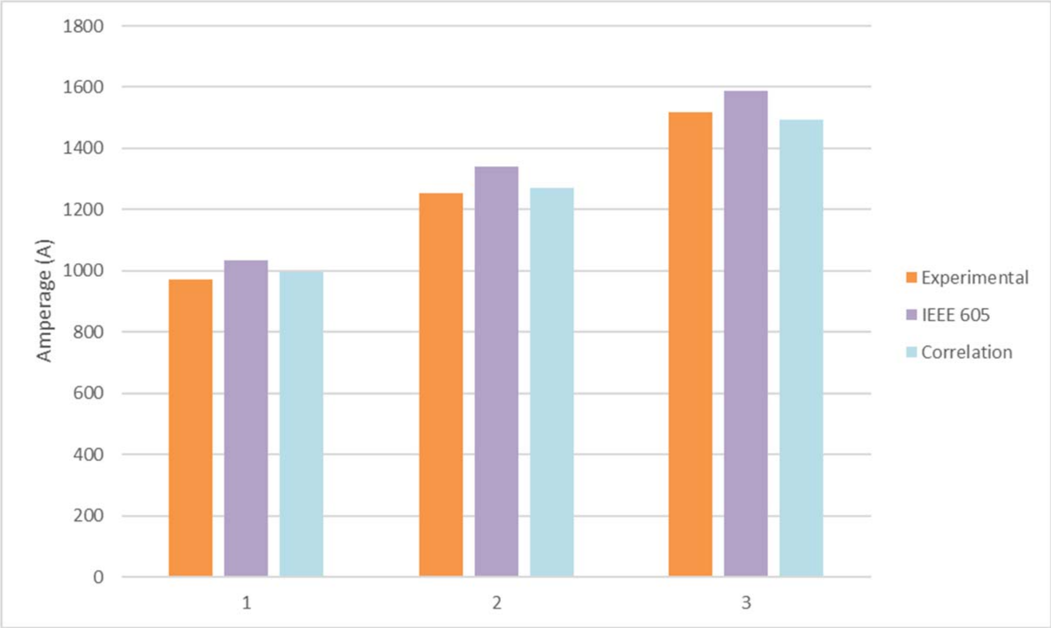
Effect on Ampacity

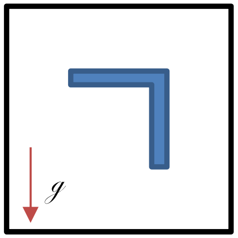




Case	Temp Rise	Experimental Current	IEEE 605 Current	605 – Exp. Error	New Method Current	New – Exp. Error
1	70	1156	1228	+6.2%	1163	+1.8%
2	109	1509	1576	+4.4%	1471	-1.4%
3	144	1775	1842	+3.8%	1708	-2.8%

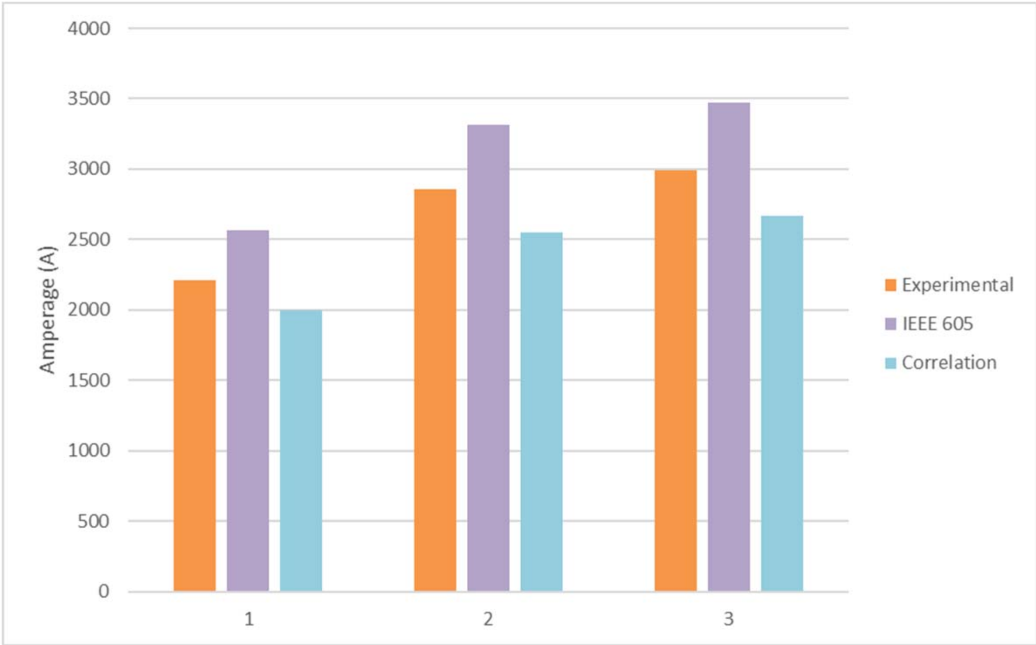
Effect on Ampacity

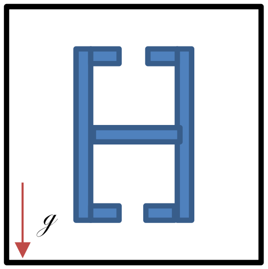




Case	Temp Rise	Experimental Current	IEEE 605 Current	605 – Exp. Error	New Method Current	New – Exp. Error
1	51	971	1033	+6.4%	997	+2.7%
2	81	1253	1339	+6.9%	1272	+1.5%
3	111	1517	1588	+4.7%	1493	-1.6%

Effect on Ampacity





Case	Temp Rise	Experimental Current	IEEE 605 Current	605 – Exp. Error	New Method Current	New – Exp. Error
1	49	2209	2568	+16.3%	2041	-7.6%
2	77	2856	3311	+16.0%	2599	-9.0%
3	85	2989	3473	+16.2%	2722	-8.9%

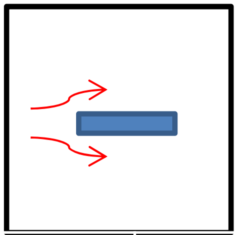
Effect on Ampacity

Assumptions

- Air properties are interpolated from Table C.1
- Skin effect factors are taken from the Aluminum Electrical Conductor Handbook, Third Edition, 1989.

Parameter	Value
Ambient temperature	40°C
Latitude	40°N
Time of Day	12:00 noon
Elevation	Sea level
Bus direction	East-West
Wind	0.6 m/s - 90° to the conductor axis
Solar Absorptivity	0.5
Emissivity	0.5
Conductivity - Material	55% IACS - Aluminum

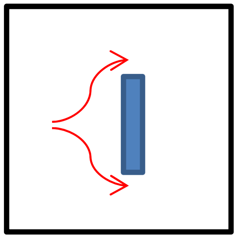
Effect on Ampacity



	Size (in)	Temperature Rise Above 40 C Ambient						
		30	40	50	60	70	90	110
Table B.2	0.25 x 3	959	1118	1253	1371	1478	1665	1828
Correlation		850	1003	1132	1245	1346	1523	1678
% Change		-11.4	-10.3	-9.7	-9.2	-8.9	-8.5	-8.2
Table B.2	0.625 x 6	2437	2855	3213	3531	3820	4337	4798
Correlation		2165	2590	2947	3261	3544	4047	4494
% Change		-11.2	-9.3	-8.3	-7.6	-7.2	-6.7	-6.3

Note: Skin Effect F1 = 1.031 at 70°C for 0.25 x 3
F1 = 1.28 at 70°C for 0.625 x 6

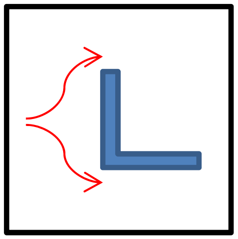
Effect on Ampacity



	Size (in)	Temperature Rise Above 40 C Ambient 30	40	50	60	70	90	110
Table B.2	0.25 x 3	959	1118	1253	1371	1478	1665	1828
Correlation		966	1131	1269	1390	1499	1688	1851
% Change		+0.70	+1.16	+1.28	+1.38	+1.42	+1.38	+1.26
Table B.2	0.625 x 6	2437	2855	3213	3531	3820	4337	4798
Correlation		2449	2898	3278	3611	3911	4442	4910
% Change		+0.49	+1.51	+2.02	+2.27	+2.38	+2.42	+2.33

Note: Skin Effect F1 = 1.031 at 70°C for 0.25 x 3
F1 = 1.28 at 70°C for 0.625 x 6

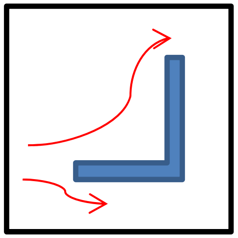
Effect on Ampacity



		Temperature Rise Above 40 C Ambient						
	Size (in)	30	40	50	60	70	90	110
Table B.6	3.25 x 3.25 x 0.25	1550	1889	2169	2412	2628	3007	3336
Correlation		1353	1695	1970	2205	2413	2774	3086
% Change		-12.7	-10.3	-9.17	-8.58	-8.18	-7.75	-7.49
Table B.6	5 x 5 x 0.375	2443	3032	3516	3936	4311	4973	5555
Correlation		2232	2833	3316	3730	4097	4738	5297
% Change		-8.6	-6.6	-5.7	-5.2	-5.0	-4.7	-4.6

Note: Skin Effect F1 = 1.024 at 70°C for 3.25 x 3.25 x 0.25
F1 = 1.175 at 70°C for 5 x 5 x 0.375

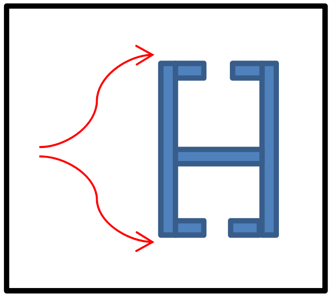
Effect on Ampacity



		Temperature Rise Above 40 C Ambient						
	Size (in)	30	40	50	60	70	90	110
Table B.6	3.25 x 3.25 x 0.25	1550	1889	2169	2412	2628	3007	3336
Correlation		1177	1517	1788	2018	2221	2575	2883
% Change		-24.1	-19.7	-17.6	-16.3	-15.5	-14.4	-13.6
Table B.6	5 x 5 x 0.375	2443	3032	3516	3936	4311	4973	5555
Correlation		1908	2511	2987	3393	3752	4381	4932
% Change		-21.9	-17.2	-15.0	-13.8	-13.0	-11.9	-11.2

Note: Skin Effect F1 = 1.024 at 70°C for 3.25 x 3.25 x 0.25
F1 = 1.175 at 70°C for 5 x 5 x 0.375

Effect on Ampacity



		Temperature Rise Above 40 C Ambient						
	Size (in)	30	40	50	60	70	90	110
Table B.8	6 x 4 x 0.375	3572	4470	5211	5856	6434	7453	8349
Correlation		3217	4186	4914	5533	6079	7025	7845
% Change		-9.9	-6.4	-5.7	-5.5	-5.5	-5.7	-6.0
Table B.8	8 x 8 x 0.5	5922	7594	8963	10152	11219	13110	14786
Correlation		5572	7407	8833	10032	11083	12895	14458
% Change		-5.9	-2.5	-1.5	-1.2	-1.2	-1.6	-2.2

Note: Skin Effect F1 = 1.080 at 70°C for 6 x 4 x 0.375
F1 = 1.26 at 70°C for 8 x 8 x 0.5

Effect on Ampacity

Table	Impact	Resulting Tables
B.2 – Single Al rect. w/ sun	Update	Single horizontal Al rect. w/ sun
		Single vertical Al rect. w/ sun
B.3 – Single Al rect. w/o sun	Update	Single horizontal Al rect. w/o sun
		Single vertical Al rect. w/o sun
B.4 – Al tubular sch. 40	Not affected	-
B.5 – Al tubular sch. 80	Not affected	-
B.6 – Single Al angle	Update	Single Al angle closed
		Single Al angle open
B.7 – Double AL angle	Not affected	-
B.8 – Al Integral web	Update	Al Integral web

Effect on Ampacity

Table	Impact	Resulting Tables
B.9 – Single Cu rect. w/ sun	Update	Single horizontal Cu rect. w/ sun
		Single vertical Cu rect. w/ sun
B.10 – Single Cu rect. w/o sun	Update	Single horizontal Cu rect. w/o sun
		Single vertical Cu rect. w/o sun
B.11 – Cu tubular sch. 40	Not affected	-
B.12 – Cu tubular sch. 80	Not affected	-
B.13 – Double Cu channel	Not affected	-

Currently 12 ampacity tables. Recommended changes will result in 17 tables.

Agenda

1. Project Overview & Refresher
2. Forced Convection Correlations
3. Natural Convection Correlations
4. Effect on Calculated Ampacity
5. **Discussion / Questions**

Questions?