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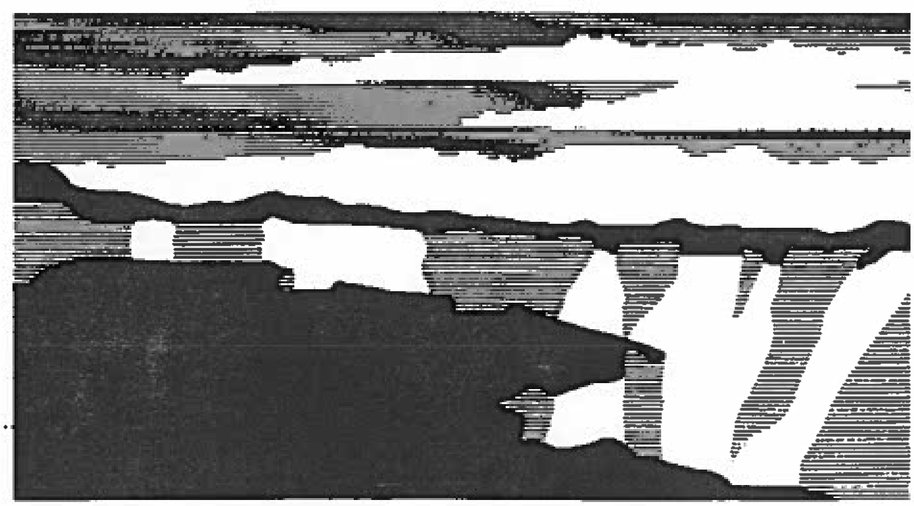

Los Alamos
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The Effect of Discharge Channel Parameters and Pixel Size on Thermal Plume from a River Cooling System

by

George Auchampaugh

I. Introduction

Commercial nuclear and coal-fired power plants generate tremendous amounts of heat; some is converted into electrical energy but most is dissipated in a surface or tower cooling system. Four surface cooling systems can be differentiated by the body of water used to cool the heated water: a river, a shallow pond, a deep pond or lake, or an ocean or estuary. The choice of cooling system is dictated primarily by economics and environmental regulations. However, all surface cooling systems create a thermal plume in the water. The size and thermal properties of the plume depend not only on power level but local meteorology, and, for surface cooling systems, on geometry and dynamics of the body of water, and on geometry of and flow rate in the channel leading to the body of water.

The Multispectral Thermal Imager (MTI) instrument being built for the DOE nonproliferation program basically provides a 2-dimensional (2D) image of the plume. Without ancillary ground support data, this is all that will be available to interpret the thermal image. Many of the parameters that might affect the image will be unknown. How important are these parameters for extracting information about the operating condition of the plant? In this report we develop a statistic to measure thermal output from a power plant and present results of a sensitivity study on discharge channel properties and pixel size for a river cooling system.

The calculations were done on a SPARCstation 10/514 using the time-dependent, 3-dimensional (3D), fluid dynamic code FLOW-3D® from Flow Science, Inc.

II. River Model

The model is based on the Bull Run power plant near Knoxville, Tennessee. This is a coal-fired power plant cooled by the Clinch River. The plant produces about 2360 MW of thermal power and dissipates about 1200 MW of it into the river. A T-shaped baffle divides the intake channel from the outfall channel as shown in Fig. 1. This airborne image was taken on March 31, 1994, with a Daedalus 1268 scanner at an altitude of 610 m. The width of the plume is constrained by the width of the river, which is about 300 m wide downstream of the discharge channel. This image shows only a portion of the plume, but the surface area is still large, more than 0.4 km^2. Unfortunately, the entire plume was not imaged. The river has a nominal flow rate of 135 m^3/s, which is highly variable and can be zero. The main channel of the river is about 120 m wide by 14 m deep, which, for a nominal flow rate of 135 m^3/s, corresponds to a water velocity of 0.08 m/s. The difference between the intake and outfall water temperatures is about 14 K. The river is fairly cold year around and in spring has an average temperature of about 285 K

The parameters for the model of the river are given in Table I. We chose a river temperature of 295 K instead of the average spring temperature of 285 K because 295 K has been used in other studies and the exact value is not as important as the temperature difference between the outfall channel and the river. In the model, the outfall channel is perpendicular to the river flow, and it does not have a baffle. There is no intake channel.

The mesh geometry for the river is shown in Fig. 2. The cells are rectangular parallelepipeds and are 1 m thick in the z direction. The mesh size is variable in the other directions. For the x direction, the mesh size starts at 5 m at x = 0 and increases to 10 m at x = 1600; for the y direction, the mesh size starts at 5 m at y = 0 and increases to 7.5 m at y = 180. The cells from 0 to 25 m in the x direction have a uniform width of 5 m. The number of cells in the x, y, and z directions is 160, 15, and 5, respectively.

II. Problem Definition

The relation between power dissipated in a channel of water flowing through a heat source and the rise in temperature of the water is given by

$$P_d = 4.2\dot{V}\,(T_{outfall} - T_{intake}),$$

$$\dot{V} = W_c D_c U_{dis}$$

where P_d is the power dissipated in megawatts, W_c and D_c are the width and depth of the channel in meters, U_{dis} is the discharge velocity in meters/second, $\dot{V}$ is the volume flow rate in cubic meters/second, and T_{intake} and $T_{outfall}$ are the intake and outfall temperatures in kelvin. For the study on the effects of channel parameters for the thermal plume, we varied W_c, D_c, and U_{dis} in such a way as to keep P_d fixed for a given $\Delta T = T_{outfall} - T_{intake}$. In our problems, $\Delta T = 14$ K, $T_{intake} = 295$ K, and P_d = 178, 445, 890, 1335, and 1780 MW.

The values of the channel parameters considered for the five power levels are given in Table II. A problem is defined by selecting P_d and reading from the Table the corresponding values for W_c, D_c, and U_{dis}. For example, for P_d = 1780 MW, and selecting W_c = 5 m and D_c = 2 m, U_{dis} = 3.027 m/s.

For the pixel study, the calculated surface image is resampled into various pixel sizes. The size of a pixel is chosen to be a multiple of the width and length of the model; namely, 5, 10, 20, 40, and 80 m for δx and 5, 10, and 20 m for δy. In this way, edge effects at the boundaries y = 0 and 180 are avoided. The only edge effects are the upstream and downstream boundaries of the plume. And, these only become important when the number of pixels at these boundaries is a large fraction of the total number. The combinations used for pixel sizes are: 5x5, 10x10, 20x20, 40x20, and 80x20. This range of pixel sizes overlaps those of the MTI thermal bands. Resampling is done on the basis of temperature and not irradiance.

The total number of problems run was 51. Each problem was run for 9000 model seconds. A thermal image was recorded for all five z levels every 3000 model seconds. The clock time per problem varied from an average of 12000 seconds for the P_d = 178 problems to an average of 38000 seconds for the P_d = 1780 problems. The total time for all problems was about 400 hours.

FLOW-3D can handle heat transfer at the surface,[1] but the option was not used for these problems. Similar problems with heat transfer have shown that the average temperature of the plume is only slightly reduced for typical meteorological conditions and that the size of the plume is smaller. Wind, for example, causes more vertical mixing of the heated surface layer with the cooler water below the surface, resulting in a smaller plume. A subset of the problems should be rerun to quantify the effect of heat transfer on plume characteristics.

FLOW-3D has several options to handle turbulence. The one selected and recommended in the FLOW-3D manual is the two-equation κ&ε turbulence model. This model solves the transport equations for turbulence energy and dissipation energy rate and, with judicious choice of boundary conditions, handles a wide variety of turbulence problems. For our problems, we assume at the inflow boundary a turbulence energy of 0.0845 J/kg and a dissipation rate of 0.01 J/kg/s, which translate into a turbulence length scale of 0.27 m. We have found that the exact value of these parameters is not critical for large-scale problems, such as considered in this study. However, a more careful selection of these parameters would be warranted if we were modeling the near-field properties of the plume.

A typical FLOW-3D input file for the 1335-MW problem with a channel width of 5 m and a channel depth of 2 m is listed in Table III. This input file would produce just thermal plots, with and without contour levels, at the five z levels. However, the data file produced by FLOW-3D contains information on all parameters (pressure, velocity, viscosity, etc.) tracked in the calculation and can be postprocessed to create 2D and 3D data files of these parameters. In our study we analyzed just the thermal surface image.

III. Statistic Evaluated

The statistic evaluated for use as an indicator of power is the temperature difference averaged over the surface area of the plume, defined as

$$\langle TD(P, W_c, D_c)\rangle = \frac{\sum_{i=1}^{N}\left(T_i(P, W_c, D_c) - T_r\right)A_i(P, W_c, D_c) \,/\, A_t(P, W_c, D_c)}{N}$$

where,

$$A_i = W_c D_c$$

$$A_t(P, W_c, D_c) = \sum_{i=1}^{N} A_i(P, W_c, D_c)$$

and N is the number of pixels for which $T_i - T_r > T_{thres}$. T_{thres} is a threshold for accepting the pixel as part of the thermal image. Until the pixel has a temperature difference greater than this value, it cannot be distinguished from a pixel unperturbed by the heated water. For the thermal channels on MTI, T_{thres} is probably better than 1 K.

IV. Results For Different Channel Properties

The results of the calculations can be presented in tabular and graphical formats. Figures 3 through 6 show calculations of the 1335-MW thermal images for four different channel parameters. Figures 3 and 4 show the results for a 5-m wide channel at two channel depths. Figs. 5 and 6 show the results for a 20-m-wide channel at the same depths. The large-scale features of the images are similar; that is, the images fill the entire width of the model and have almost the same length. However, significant differences occur near the discharge channel (lower left-hand corner of an image). The widths and lengths of the hot portion of the jet in the image are different, reflecting the different channel properties. The high velocity of the problem in Fig. 3 causes a recirculation zone near the channel that is less noticeable in the other figures.

Average temperatures versus channel parameters for the five power levels at $T_{thres} = 0.5$ K are presented in Tables IV through VIII. A subset of these data, which show the effect on the average temperature for different assumptions about our knowledge of channel parameters, are presented in Figs. 7 through 9. The pixel size is 20 x 20 m^2. In Fig. 7, we know the depth of the channel is 4 m but do not know its width. Lack of knowledge about the width of the channel does not introduce as large an uncertainty in the temperature at low power levels, less than 400 MW, as it does at high power levels. In Fig. 8, we know the width of the channel is 10 m but do not know its depth. In this case, the uncertainty is less at high power levels. However, at low power levels the uncertainty is larger than if the depth is known. Finally, in Fig. 9, we know both the width and depth of the channel. There now is some measurable uncertainty in the temperature at low power levels but still considerably less than at high power levels. Knowledge of the width of the channel appears to have more impact on the temperature uncertainty than the depth of the channel. Fortunately, this is the parameter that we can obtain from the MTI visible bands, providing, of course, the channel is not buried.

V. Results For Different Pixel Sizes

Average temperatures versus pixel size for $T_{thres} = 0.5$ K are presented in Tables IV through VIII. In Figs. 10 and 11 we select a subset of these data to show the effect of pixel size on average temperature. The pixel size does not appear to have much influence on the temperature, as shown in Fig. 10, because the upstream and downstream pixels, those whose temperature can be affected by pixel size, are few in number, compared with the total number of pixels as shown in Fig. 11.

V. Results For Different Thresholds

The average temperature difference plotted as a function of the threshold parameter T_{thres} is shown in Fig. 12. Aside from the 178-MW cases, the temperature decreases with increasing threshold. This is what would be expected because the plume is now being defined by fewer and higher temperature pixels. The extreme situation is illustrated with the 178-MW cases. Instead of the temperature decreasing over the full range of thresholds, it starts to increase at a threshold of about 0.6 K and reaches a value greater than that at zero threshold. This is because at a threshold of 1.5 K the number of pixels is very few (on the order of four), and they are located at the exit to the channel where the temperature of the water is highest. Consequently, at high threshold the power level may no longer be uniquely related to temperature and the change in temperature with power level is less.

VI. Conclusions

Several conclusions can be drawn from this limited study.

(1) The deduced power level is a strong function of the parameters of the discharge channel, particularly at power levels above about 500 MW.

(2) The width of the discharge channel appears to be a more important parameter for reducing the uncertainty in deduced power level than the depth of the channel.

(3) The thermal plume is large enough, even for the 178-MW cases, that the uniqueness between average temperature and power level is unaffected by pixel size, at least for MTI values of threshold.

References

1. Auchampaugh, G, "Energy Transfer at Air/Water Interface of a Body of Water," LAUR-94-3180, Sept. 1994.

Table I: River Model Parameters

Parameter	Value
Width (m)	180
Depth (m)	10
Length (m)	1600
Velocity (m/s)	0.08
Temperature (K)	295

Table II: Channel Parameters

P_d (MW)	W_c (m)	D_c (m)	U_{dis} (m/s)
1780	5, 10, 20	2	3.027, 1.514, 0.757
1780	5, 10, 20	4	1.514, 0.757, 0.378
1780	5, 10, 20	6	1.009, 0.505, 0.252
1780	5, 10, 20	8	0.757, 0.378, 0.189
1780	5, 10, 20	10	0.605, 0.303, 0.151
1335	5, 10, 20	2	2.270, 1.135, 0.568
1335	5, 10, 20	4	1.135, 0.568, 0.284
1335	5, 10, 20	6	0.757, 0.378, 0.189
890	5, 10, 20	2	1.514, 0.757, 0.378
890	5, 10, 20	4	0.757, 0.378, 0.189
890	5, 10, 20	6	0.505, 0.252, 0.126
445	5, 10, 20	2	0.757, 0.378, 0.189
445	5, 10, 20	4	0.378, 0.189, 0.095
445	5, 10, 20	6	0.252, 0.126, 0.063
178	5, 10, 20	2	0.303, 0.151, 0.076
178	5, 10, 20	4	0.151, 0.076, 0.038
178	5, 10, 20	6	0.101, 0.050, 0.025

Table III: Prepin.inp File For FLOW-3D. P_d = 1335 MW, W_c = 5 m, And D_c =2 m

```
/data3/flowlib/3d_river_new/u08/dt14/w180/p1335a52u15: no heat transfer, full turbulence
$xput
 remark  = 'units are mks',
  ilims = 1,        iprop   = 1,      icolor = 2,
 remark = 'for now use itb=1 until bug fixed',
  itb   = 1,        iwsh    = 1,      ifrho=1,
  epsadj = 1.0,      avrck   = -2.1,
  twfin  = 9000.,     prtdt = 10000.0,     pltdt  = 1000.,
  ifenrg = 3,        ihtc  = 0,         imphtc = 0,
  wt = 1,  rwall(6)  = 0.0,
  wb = 2,  rwall(5)  = 0.0,
  wl = 6,            tbct(1,1) = 295.,
  wr = 5,  flhtr=11.,  tbct(1,2) = 295.,
  wf = 6,            tbct(1,3) = 309.,  vbct(1,3) = 2.2704,
        tkebct(1,3) = 0.0845, dtkbct(1,3) = 0.01,
  wbk = 2,  rwall(4)  = 0.0,
  gz  = -9.80665, ui = 0.08,
  ipr = 6,   iadix = 0, iadiy = 0, iadiz = 1,
  ifvis = 3, ipdis=1, iduml = 1, delt=90.,
$end
$limits
 itflmx=200,
$end
$props
  rhof = 998.2,       mui = 0.001005,
  thexfl = 2.119e-4, tstar=295.0, cv1= 4181.9,thc1=0.597,
$end
$mesh
  nxcelt = 160,
   px(1) = 0.0,  sizex(1) = 5.,
   px(2) = 10.0,  sizex(2) = 5.,
   px(3) = 20.0,  sizex(3) = 5.,
   px(4) = 1600., sizex(4) = 10.,
  nycelt = 15,
   py(1)  = 0.0,  sizey(1) = 5.,
   py(2) = 180.0, sizey(2) = 7.5,
  nzcelt = 5,
   pz(1)  = 0.0,
   pz(2) = 10.0,
$end
$obs
  nobs = 0,
$end
$fl
  presi = 0.0,
  remark = 'remove flht when bug for itb is fixed in next version',
  flht = 10.,
$end
$bf
  nbafs = 3,
  ibfo(1,1) = 1,
   bcy(1)  = 1.0,      bcc(1) = 0.0, bxh(1) = 10.,
  ibfo(1,2) = 2,
   bcy(2)  = 1.0,      bcc(2) = 0.0, bxl(2) = 15.,
  ibfo(1,3) = 3,
   bcy(3) =  1.0,      bcc(3) = 0.0, bxl(3) = 10.,  bxh(3) = 15.,
   bzh(3) = 8.,
$end
$temp
  tempi = 295.0,
$end
$grafic
  nvplts = 1,
   contpv(1) = 'tn', iperv(1) = 1, kv1(1) = 6, kv2(1) = 6,
  ncplts = 1, qmn(1) = 295., qmx(1) = 309., ncc(1) = 14,
   contyp(1) = 'tn', iperc(1) = 1, kc1(1) = 6, kc2(1) = 6,
$end
$parts
$end
```

Table IV: Average Temperature Difference (K) for P_d = 178 MW and T_{thres} = 0.5 K

Channel Parameters												
Width	Depth	Flow	Pixel Size									
(m)	(m)	(m^3/s)	5 x 5	10 x 10	20 x 20	40 x 20	80 x 20	5 x 5	10 x 10	20 x 20	40 x 20	80 x 20
5	2	0.303	0.306	0.305	0.304	0.301	0.303	5628	1409	352	177	87
5	4	0.151	0.288	0.288	0.286	0.286	0.280	5331	1334	334	166	84
5	6	0.101	0.271	0.271	0.268	0.268	0.262	5576	1395	350	174	88
10	2	0.151	0.313	0.313	0.309	0.311	0.313	5498	1373	346	171	84
10	4	0.076	0.293	0.293	0.289	0.290	0.281	5285	1321	333	165	84
10	6	0.051	0.278	0.278	0.276	0.274	0.264	5230	1308	327	164	84
20	2	0.076	0.316	0.315	0.313	0.314	0.312	5561	1390	349	173	86
20	4	0.038	0.297	0.296	0.293	0.295	0.286	5306	1328	334	165	84
20	6	0.025	0.279	0.278	0.278	0.268	0.272	5119	1278	319	164	80

Table V: Average Temperature Difference (K) for P_d = 445 MW and T_{thres} = 0.5 K

Channel Parameters												
Width	Depth	Flow	Pixel Size									
(m)	(m)	(m^3/s)	5 x 5	10 x 10	20 x 20	40 x 20	80 x 20	5 x 5	10 x 10	20 x 20	40 x 20	80 x 20
5	2	0.757	0.818	0.816	0.817	0.814	0.819	8610	2155	538	270	134
5	4	0.378	0.932	0.932	0.931	0.935	0.930	8596	2148	537	267	134
5	6	0.252	0.935	0.934	0.934	0.940	0.922	8575	2146	536	266	135
10	2	0.378	1.001	1.000	0.996	1.004	1.003	8624	2157	541	268	134
10	4	0.189	0.970	0.972	0.968	0.974	0.957	8568	2138	536	266	135
10	6	0.126	0.927	0.927	0.926	0.930	0.912	8559	2139	535	266	135
20	2	0.189	1.039	1.038	1.032	1.050	1.031	8619	2156	542	266	135
20	4	0.095	0.982	0.982	0.983	0.985	0.967	8560	2138	534	266	135
20	6	0.025	0.279	0.278	0.278	0.268	0.272	5119	1278	319	164	80

Table VI: Average Temperature Difference (K) for $P_d = 890$ MW and $T_{thres} = 0.5$ K

Channel Parameters			Pixel Size									
Width (m)	Depth (m)	Flow (m^3/s)	5 x 5	10 x 10	20 x 20	40 x 20	80 x 20	5 x 5	10 x 10	20 x 20	40 x 20	80 x 20
5	2	1.514	1.223	1.223	1.221	1.226	1.230	10434	2609	653	325	162
5	4	0.757	1.524	1.526	1.525	1.522	1.507	10197	2547	637	319	161
5	6	0.504	1.703	1.704	1.701	1.695	1.683	10195	2548	638	320	161
10	2	0.757	1.572	1.572	1.574	1.566	1.555	10203	2552	637	320	161
10	4	0.378	1.812	1.811	1.804	1.826	1.785	10166	2542	638	315	161
10	6	0.252	1.836	1.837	1.831	1.851	1.809	10167	2541	637	315	161
20	2	0.378	1.925	1.926	1.921	1.939	1.894	10155	2538	636	315	161
20	4	0.189	1.922	1.921	1.918	1.932	1.888	10139	2536	635	315	161
20	6	0.126	1.875	1.875	1.867	1.885	1.841	10139	2534	636	315	161

Table VII: Average Temperature Difference (K) for $P_d = 1335$ MW and $T_{thres} = 0.5$ K

Channel Parameters			Pixel Size									
Width (m)	Depth (m)	Flow (m^3/s)	5 x 5	10 x 10	20 x 20	40 x 20	80 x 20	5 x 5	10 x 10	20 x 20	40 x 20	80 x 20
5	2	2.270	1.562	1.560	1.558	1.556	1.556	11478	2873	719	360	180
5	4	1.135	1.812	1.812	1.819	1.816	1.786	11260	2815	701	351	178
5	6	0.757	2.091	2.090	2.098	2.095	2.061	11254	2815	701	351	178
10	2	1.135	1.886	1.887	1.891	1.879	1.862	11387	2846	710	357	180
10	4	0.568	2.268	2.268	2.269	2.262	2.237	11207	2802	700	351	177
10	6	0.378	2.407	2.409	2.409	2.405	2.366	11228	2804	701	351	178
20	2	0.568	2.362	2.362	2.362	2.355	2.343	11202	2800	700	351	176
20	4	0.284	2.548	2.547	2.548	2.541	2.513	11202	2801	700	351	177
20	6	0.189	2.539	2.538	2.540	2.533	2.491	11207	2802	700	351	178

Table VIII: Average Temperature Difference (K) for Pd = 1780 MW and Tthres = 0.5 K

Channel Parameters			Pixel Size									
Width (m)	Depth (m)	Flow (m^3/s)	5 x 5	10 x 10	20 x 20	40 x 20	80 x 20	5 x 5	10 x 10	20 x 20	40 x 20	80 x 20
5	2	3.027	1.695	1.693	1.693	1.693	1.693	11505	2880	720	360	180
5	4	1.514	2.129	2.126	2.126	2.126	2.126	11506	2880	720	360	180
5	6	1.009	2.443	2.441	2.441	2.441	2.441	11513	2880	720	360	180
5	8	0.757	2.699	2.698	2.698	2.698	2.698	11513	2880	720	360	180
5	10	0.605	2.879	2.878	2.878	2.878	2.878	11517	2880	720	360	180
10	2	1.514	2.275	2.273	2.273	2.273	2.273	11512	2880	720	360	180
10	4	0.757	2.655	2.653	2.653	2.653	2.653	11512	2880	720	360	180
10	6	0.504	2.967	2.966	2.966	2.966	2.966	11515	2880	720	360	180
10	8	0.378	3.076	3.074	3.074	3.074	3.074	11515	2880	720	360	180
10	10	0.303	3.137	3.136	3.136	3.136	3.136	11516	2880	720	360	180
20	2	0.757	2.803	2.802	2.802	2.802	2.802	11516	2880	720	360	180
20	4	0.378	3.130	3.129	3.129	3.129	3.129	11516	2880	720	360	180
20	6	0.252	3.207	3.206	3.206	3.206	3.206	11514	2880	720	360	180
20	8	0.189	3.226	3.225	3.225	3.225	3.225	11515	2880	720	360	180
20	10	0.151	3.233	3.232	3.232	3.232	3.232	11516	2880	720	360	180

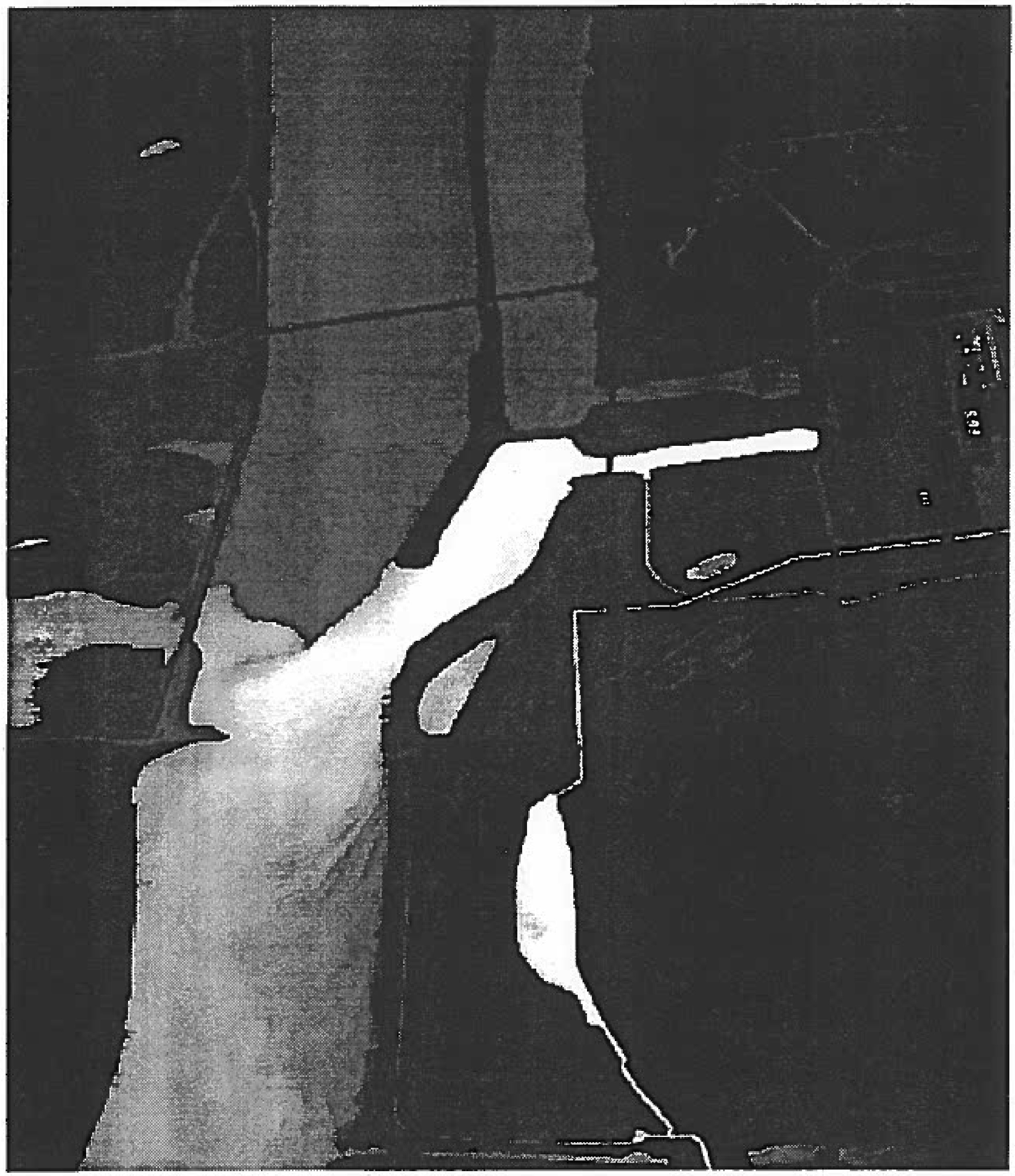

Fig. 1. Thermal image of intake and outfall from Bull Run power plant. The gray scale is calibrated so that white corresponds to high temperature and black to cold temperature.

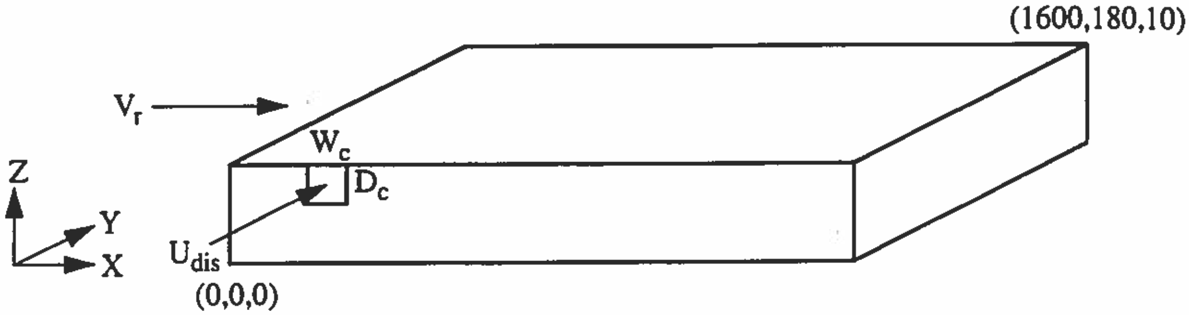

Fig. 2. Model geometry. The units of the coordinates are meters.

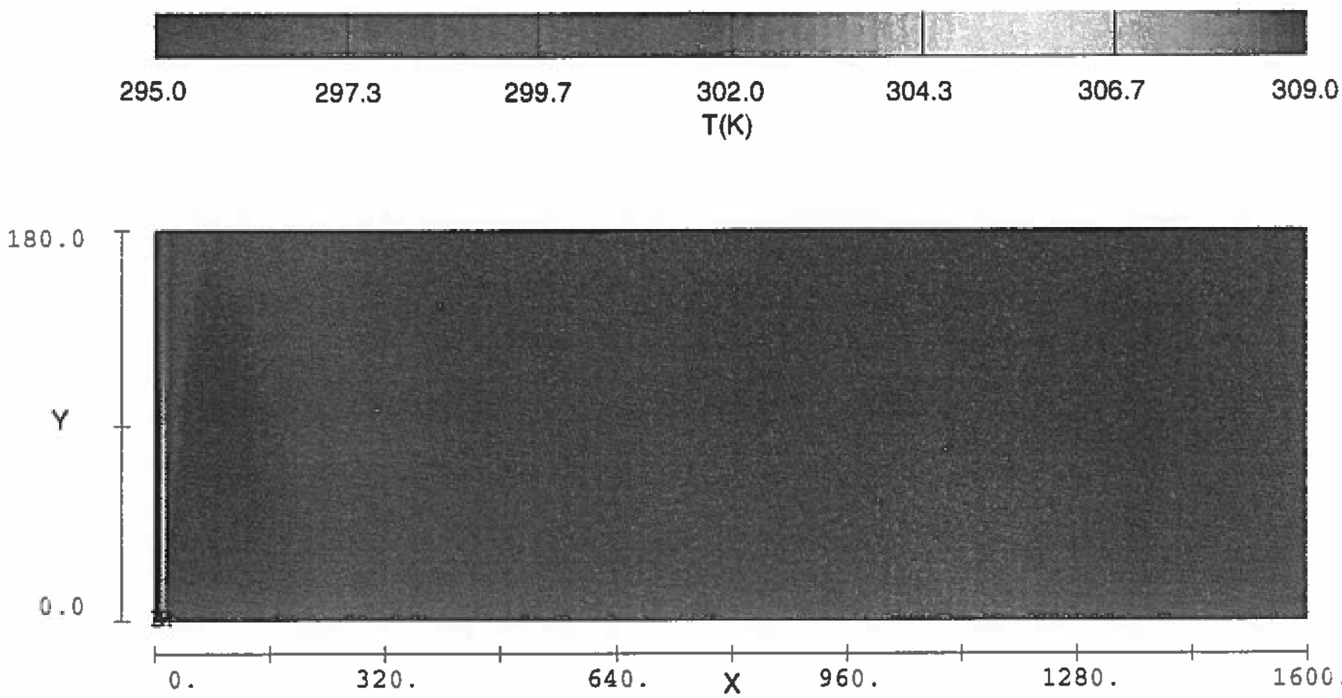

Fig. 3. Thermal surface image for P_d = 1335 MW, W_c = 5 m, D_c = 2 m, and U_{dis} = 2.270 m/s.

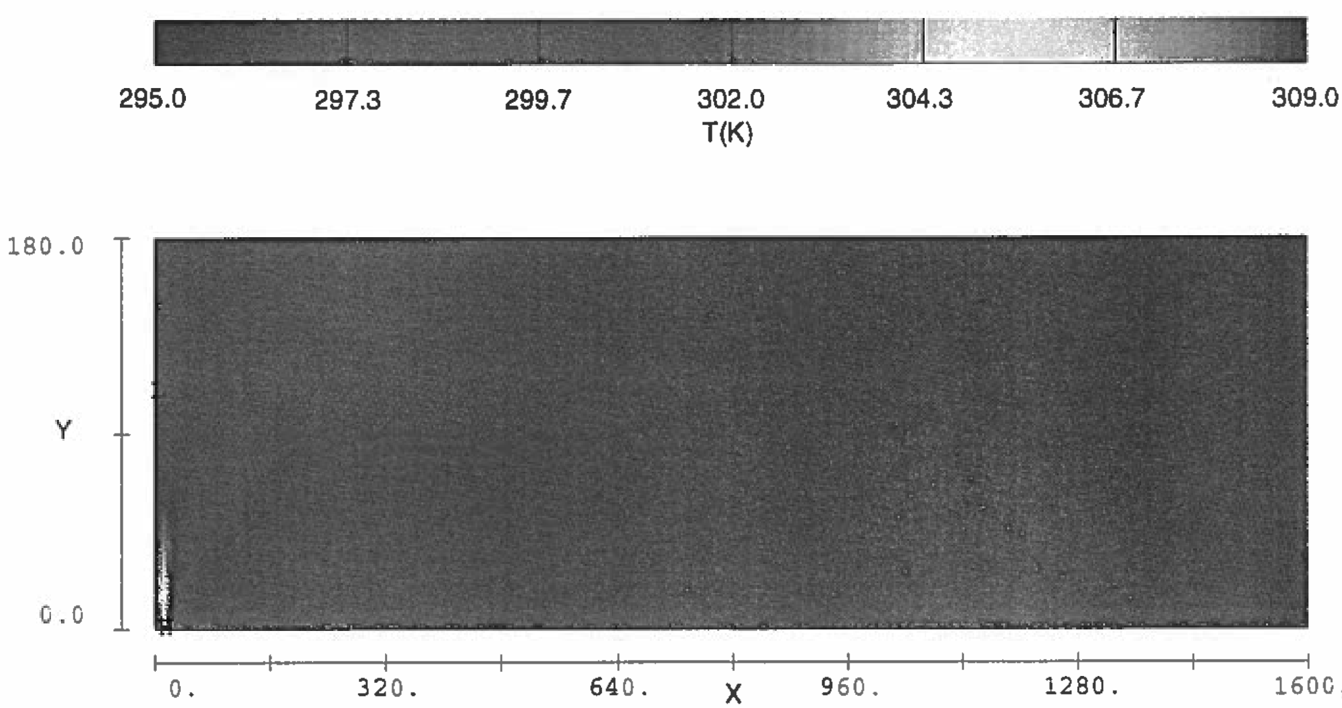

Fig. 4. Thermal surface image for P_d = 1335 MW, W_c = 5 m, D_c = 6 m, and U_{dis} = 0.757 m/s.

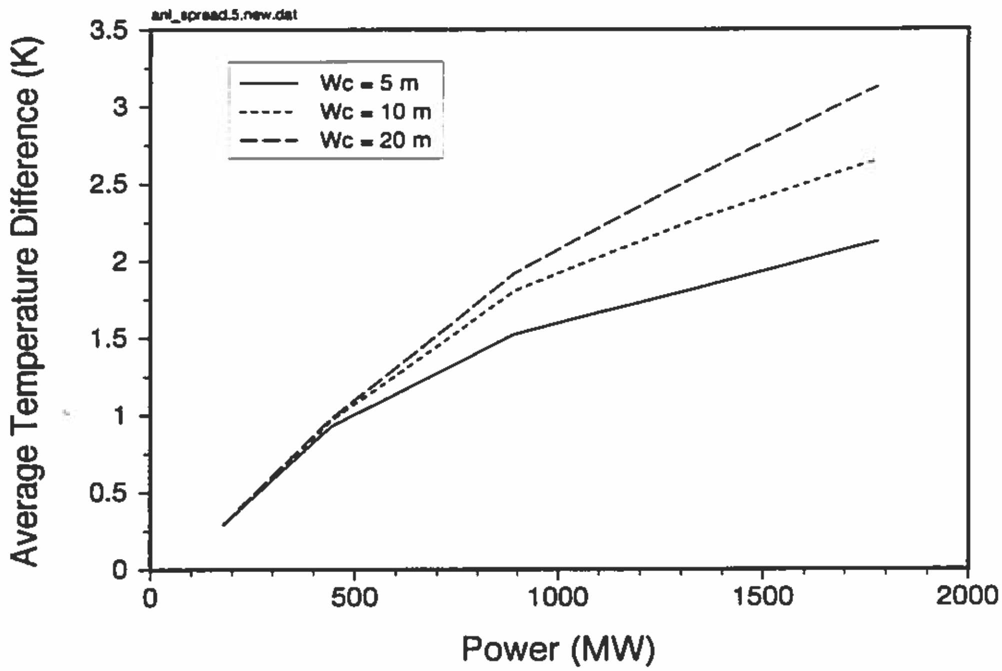

Fig. 7. Average temperature difference versus power for a channel depth of 4 m. The pixel size is 20 x 20.

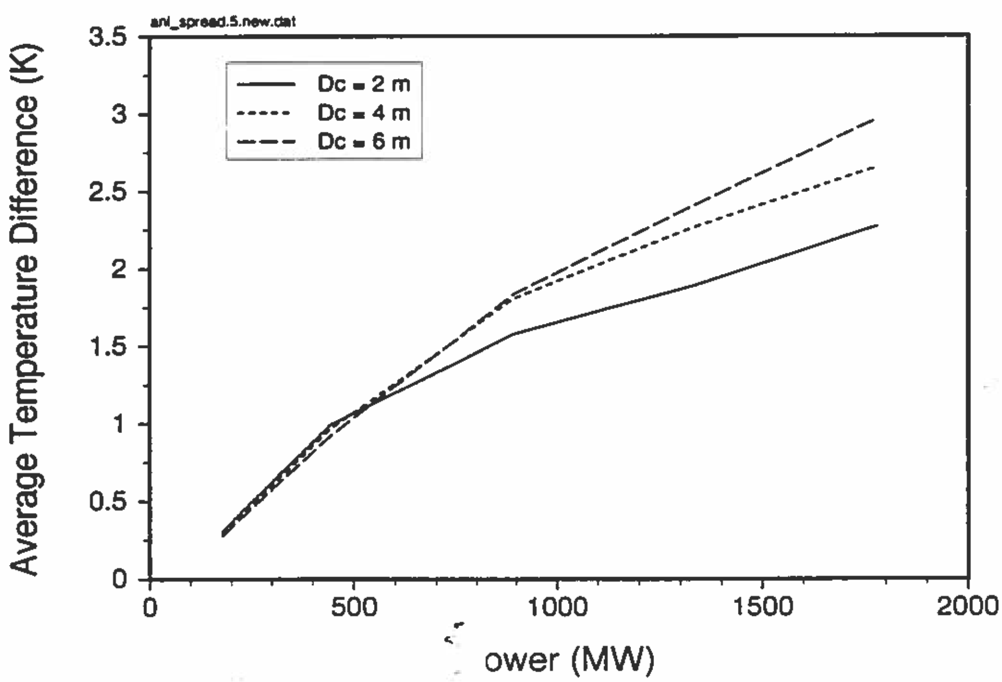

Fig. 8. Average temperature difference versus power for a channel width of 10 m. The pixel size is 20 x 20.

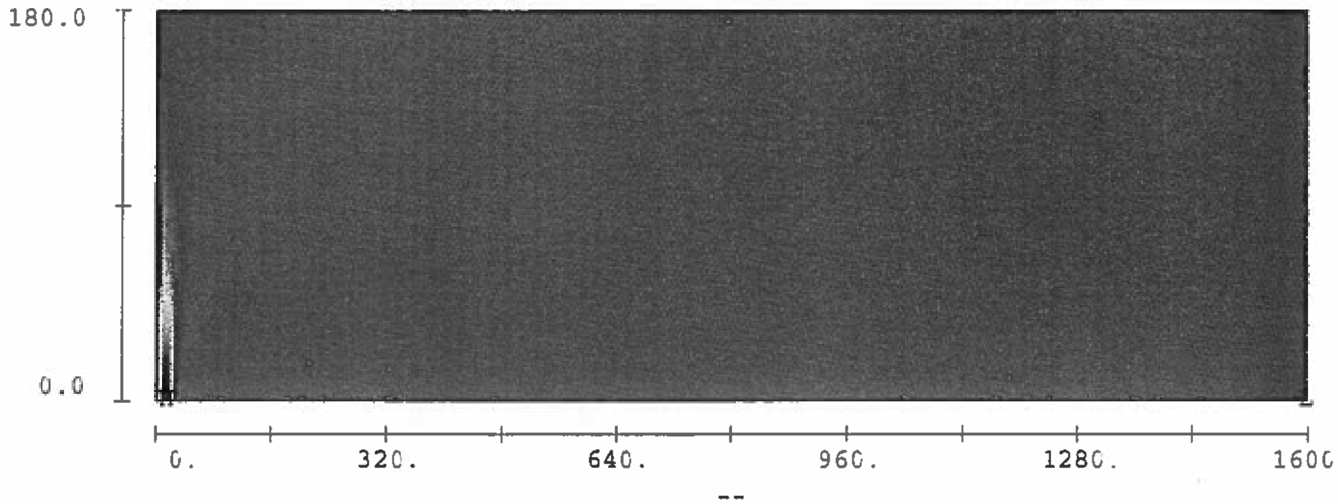

Fig. 5. Thermal surface image for P_d = 1335 MW, W_c = 20 m, D_c = 2 m, and U_{dis} = 0.568 m / s.

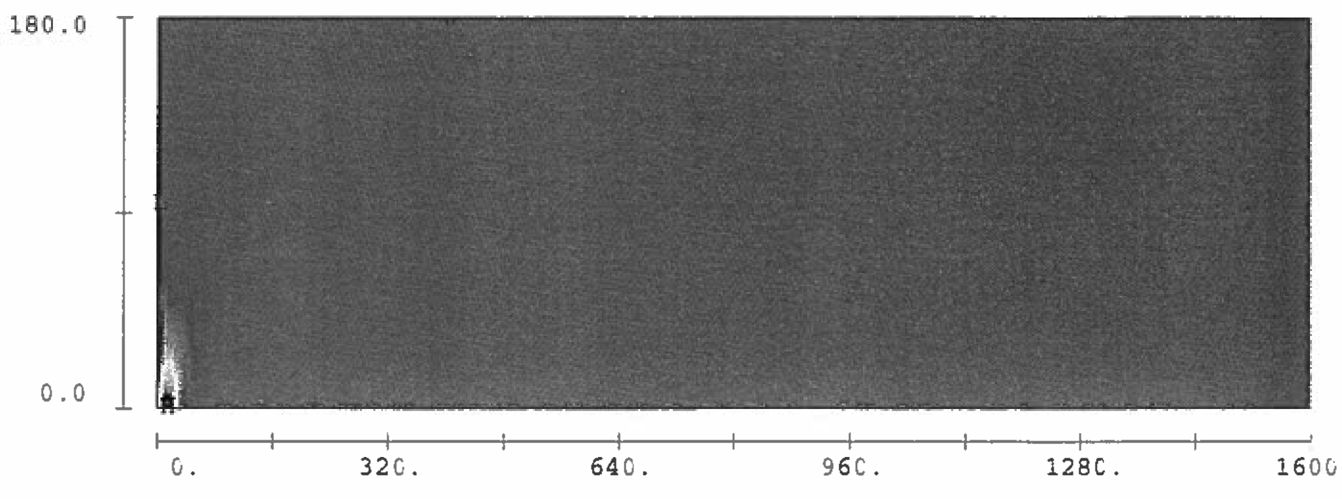

Fig. 6. Thermal surface image for P_d = 1335 MW, W_c = 20 m, D_c = 6 m, and U_{dis} = 0.189 m / s.

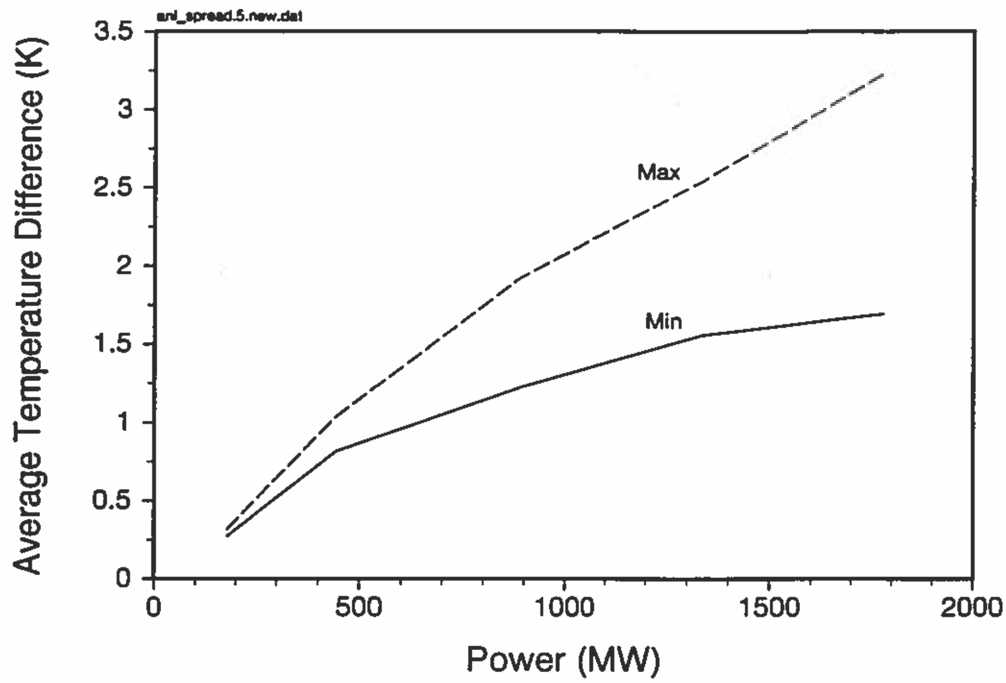

Fig. 9. Average temperature difference versus power without knowledge of channel parameters. The solid line corresponds to the minimum value and the dashed line to the maximum value for all channel parameters. The pixel size is 20 x 20.

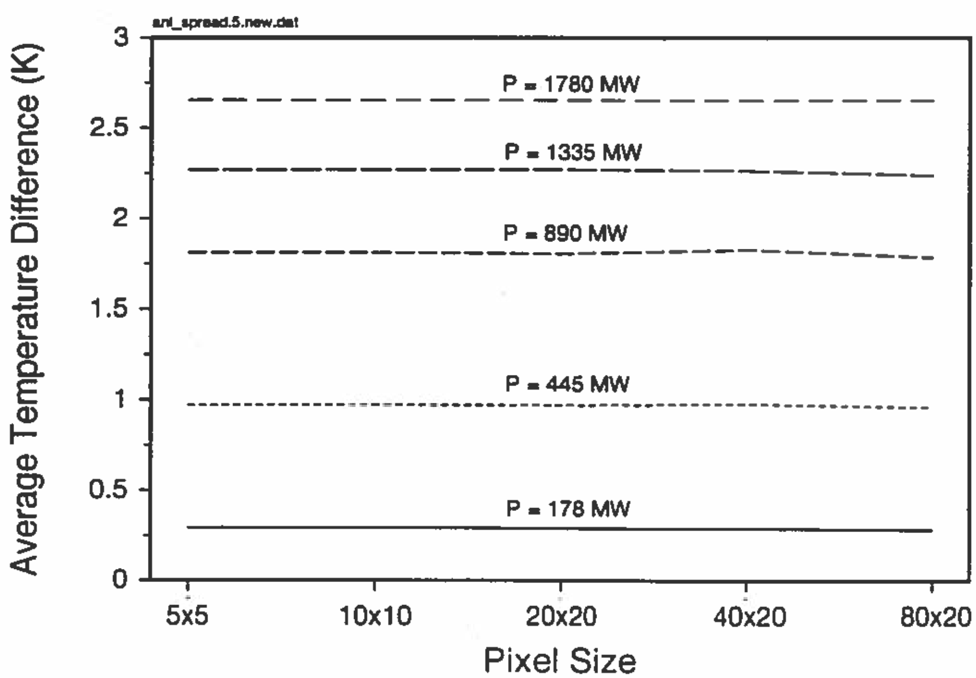

Fig. 10. Average temperature difference versus pixel size for the five power levels.

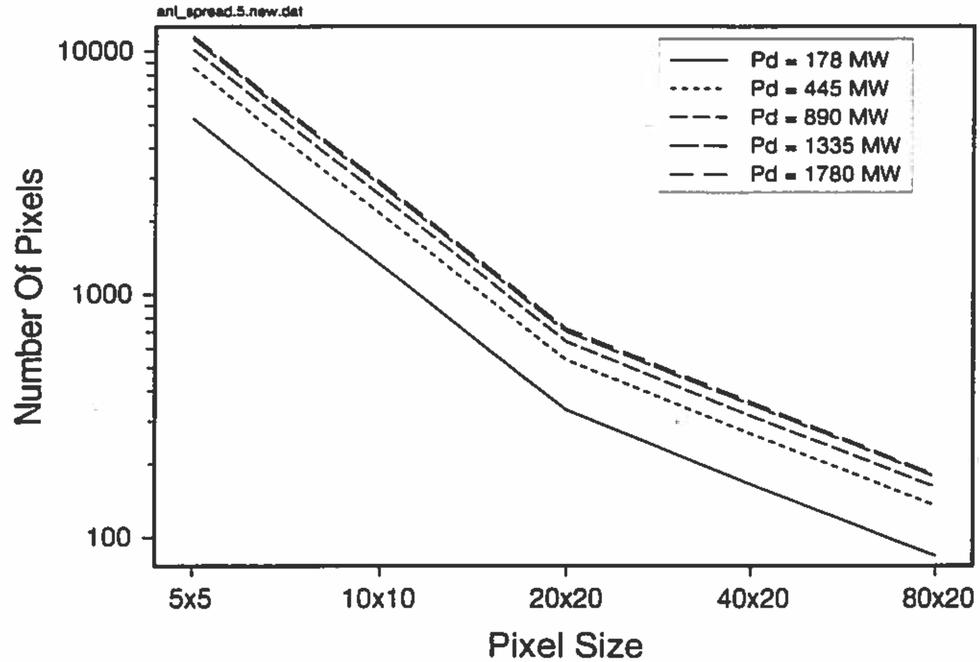

Fig. 11. The number of pixels versus pixel size for the five power levels.

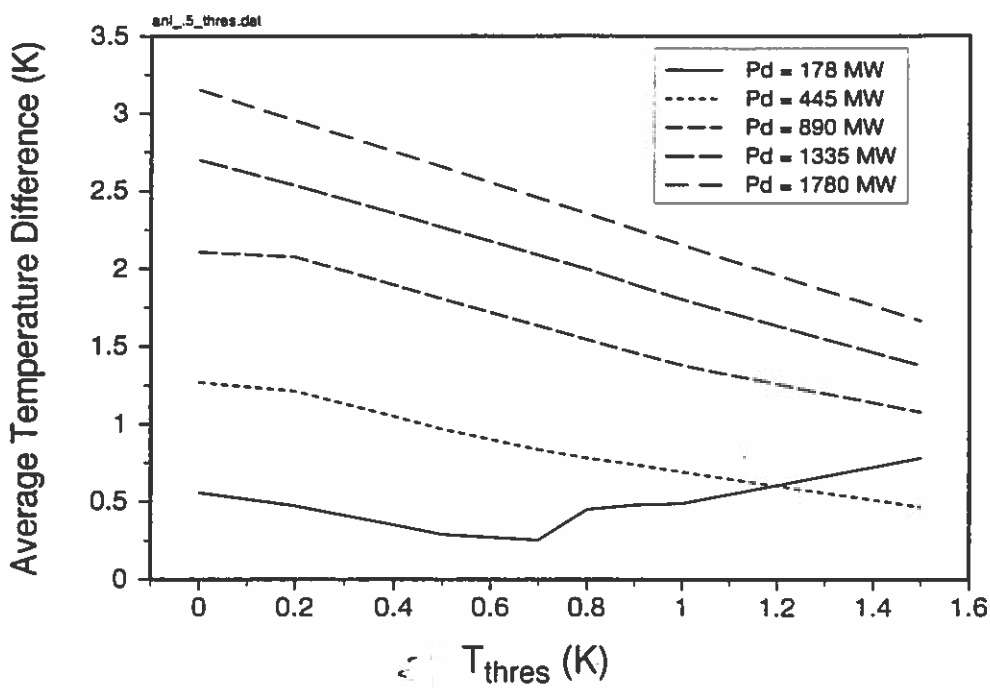

Fig. 12. Average temperature difference versus threshold temperature for the five power levels. The pixel size is 20 x 20.