REFERENCES

[1] Makmool, U., Jugjai, S., Tia, S., Vallikul, P., and Fungtammasan, B., 2007, "Performance and analysis by particle image velocimetry (PIV) of cooker-top burners in Thailand". **Energy**, Vol. 32(10), pp. 1986-1995.

[2] Dong, L.L., Leung, C.W. and Cheung, C.S., 2002, "Heat transfer characteristic of premixed butane/air flame jet impinging on an inclined flat surface", **Heat and Mass Transfer**, Vol. 39, pp. 19-26.

[3] Mishra, D.P., 2008, "An experimental study of an impinging LPG/air premixed flame", **Journal of Institution of Engineers**, Vol. 88, pp. 1-7.

[4] Sze, L.K., Cheung, C.S. and Leung, C.W., 2004, "Temperature distribution and heat transfer characteristics of an inverse diffusion flame with circumferentially arraged fuel ports", **International Journal of Heat and Mass Transfer**, Vol. 47, pp. 3119-3129.

[5] Hou, S.S. and Ko, Y.C., 2004, "Effects of heating height on flame appearance, temperature field and efficiency of an impinging laminar jet flame used in domestic gas stove", **Energy Conversion and Management**, Vol. 45, pp. 1583-1595.

[6] Jugjai, S. and Rungsimuntuchart, N., 2002, "High efficiency heat-recirculation domestic gas burners", **Experimental Thermal and Fluid Science**, Vol. 26, pp. 581-592.

[7] Mohr, J.W., Seyed-yagoobi, J. and Page, R.H., 1996, "Combustion measurements from an impinging Radial Jet Reattachment flame", **Combustion and Flame**, Vol. 106, pp. 69-80.

[8] Remie, M.J., Cremers, M.F.G., Schreel, K.R.A.M. and de Goey, L.P.H., 2006, "Flame jet properties of Bunsen-type flames", **Combustion and Flame**, Vol. 147, pp. 163-170.

[9] Li, H.B., Wong, T.T., Leung, C.W. and Probert, S.D., 2006, "Thermal performances and CO emissions of gas-fired cooker-top burner", **Applied Energy**, Vol. 83, pp. 1326-1338.

[10] Energy Policy and Planning Office, **Energy database** [Online], Available: http://www.eppo.go.th/info/index.html. [2011, July 29].

[11] Namkhat, A. and Jugjai, S., 2010, "Primary air entrainment characteristics for a self-aspirating burner: Model and experiments", **Energy**, Vol. 35, pp. 1701-1708.

[12] Tamir, A., Elperin, T. and Yotzer, S., 1989, "Performance characteristics of a gas burner with a swirling central flame", **Energy**, Vol. 14, pp. 373-382.

[13] Jugjai, S., Tia, S. and Trewetasksorn, W., 2001, "Thermal efficiency improvement of an LPG gas cooker by a swirling central flame", **International Journal of Energy Research**, Vol. 25, pp. 657-674.

[14] Hou, S.S., Lee, C.Y. and Lin, T.H., 2007, "Efficiency and emissions of a new domestic gas burner with a swirling flame", **Energy Conversion and Management**, Vol. 48, pp. 1401-1410.

[15] Seung, W.C., Young, S.K., Chung, H.J. and Young, J.C., 2010, "An experimental study on the performance optimization of a radiant burner with a surface flame structure", **Journal of Mechanical Science and Technology**, Vol. 24, pp. 923-929.

[16] Brenner, G., Pickenacker, K., Pickenacker, O., Trimis, D., Wawrzinek, K. and Webber, T., 2000, "Numerical and experimental investigation of matrix-stabilized methane/air combustion in porous inert media", **Combustion and Flame**, Vol. 123, pp. 201-213.

[17] Leonardi, S.A., Viskanta, R. and Gore, J.P., 2003, "Analytical and experimental study of combustion and heat transfer in submerged flame metal fiber burners/heaters", **Journal of Heat Transfer**, Vol. 125, pp. 118-125.

[18] Mital, R., Gore, J.P. and Viskanta, R., 1997, "A study of the structure of submerged reaction zone in porous ceramic radiant burners", **Combustion and Flame**, Vol. 111, pp. 175-184.

[19] Hanamura, K., Echigo, R. and Zhdanok, S.A., 1993, "Superadiabatic combustion in a porous medium", **International Journal of Heat and Mass Transfer**, Vol. 36, pp. 3201-3209.

[20] Weinberg, F.J., 1971, "Combustion temperature: the future?", **Nature**,Vol.233, pp. 239-241.

[21] Catapan, R.C., Oliveira, A.A.M. and Costa, M., 2011, "Non-uniform velocity profile mechanism for flame stabilization in a porous radiant burner", **Experimental Thermal and Fluid Science**, Vol. 35, pp. 172-179.

[22] Yoshizawa, Y., Sasaki, K. and Echigo, R., 1988, "Analytical study of the structure of radiation controlled flame", **International Journal of Heat and Mass Transfer**, Vol. 31, pp. 311-319.

[23] Mathis, W.M. and Ellzey, J.L., 2003, "Flame stabilization, operating range, and emissions for a methane/air porous burner", **Combustion Science and Technology**, Vol. 175, pp. 825-839.

[24] Min, D.K. and Shin, H.D., 1991, "Laminar premixed flame stabilized inside a honeycomb ceramic", **International Journal of Heat and Mass Transfer**, Vol. 34, pp. 341-356.

[25] Khanna, V., Goel, R. and Ellzey, J.L., 1994, "Measurements of emissions and radiation for methane combustion within a porous medium burners", **Combustion Science and Technology**, Vol. 99, pp. 133-142.

[26] Sathe, S.B., Peck, R.E. and Tong, T,W, 1990, "Flame stabilization and multimode heat transfer in inert porous media: a numerical study". **Combustion Science and Technology**, Vol. 70, pp. 93-109.

[27] Jones, H.R.N., 1989, **The Application of Combustion Principles to Domestic Gas Burner Design**, 1st ed., British Gas plc, London, pp. 31-33.

[28] Hardesty, D.R. and Weinberg, F.J., 1974, "Burners producing large excess enthalpies", **Combustion Science and Technology**, Vol. 8, pp.201-214.

[29] Lloyd, S.A. and Weinberg, F.J., 1974, "A burner for mixtures of very low heat content", **Nature**, Vol. 251, pp. 47-49.

[30] Weinberg, F.J., 1986, **Advance Combustion Methods**, Academic press, London, pp. 183-218.

[31] Echigo, R., 1982, "Effective energy conversion method between enthalpy and thermal radiation and application to industrial furnace", **Proceedings of the Seventh Heat Transfer Conference**, Munich, Vol. 6, pp. 361-366.

[32] Echigo, R., 1987, "Sophisticated application of radiation heat transfer", **Heat Transfer in High Technology and Power Engineering**, Hemisphere, Washington, DC, pp. 503-514.

[33] Tierney, C. and Harris, A.T., 2009, "Materials design and selection issues in ultra-lean porous burners", **Journal of the Australian Ceramic Society**, Vol.45, pp. 20-29.

[34] Howell, J.R., Hall, M.J. and Ellzey, J.L., 1996, "Combustion of hydrocarbon fuels within porous inert media", **Progress in Energy and Combustion Science**, Vol. 22, pp. 121-145.

[35] Carter, C.B. and Norton, M.G., 2007, **Ceramic Materials Science and Engineering**, Springer Science+Business Media, LLC, U.S.A., pp. 345-354.

[36] Scheffler, M. and Colombo, P., 2005, **Cellular Ceramics: structure, manufacturing, properties and applications**, WILEY-VCH Verlag GmbH&Co. KGaA, Weinheim.

[37] Nield, D.A. and Bejan, A., 2006, **Convection in porous media**, 3rd ed., Springer, U.S.A.

[38] Babkin, V.S., Korzhavin, A.A. and Bunev, V.A., 1991, "Propagation of premixed gaseous explosion flames in porous media", **Combustion and Flame**, Vol. 87, pp. 182-190.

[39] Ergun, S., 1952, "Fluid flow through packed columns", **Chemical Engineering Progress**, Vol. 48, pp. 1179-1184.

[40] Zou, R.P. and Yu, A.B., 1995, "The packing of spheres in a cylindrical container: the thickness effect", **Chemical Engineering Science**, Vol. 50, pp. 1504-1507.

[41] Kline, S.J. and McClintock, F.A., 1953, "Describing uncertainties in single-sample experiments", **Mechanical Engineering**, Vol. 75, pp. 3-8.

[42] Pritchard, R., Guy, J.J. and Connor, N.E., 1977, **Handbook of industrial gas utilization: engineering principles and practice**, Van Nostrand Reinhold Co., New York.

[43] Sullivan, J.D. and Kendall, R.M., 1992, "Thermal performance and NO_x emissions from porous surface radiant burners", **International Gas Research Conference**, pp. 1626-1634.

[44] Ozisik, M.N., 1973, **Radiative Transfer and Interactions with Conduction and Convection**, John Wiley & Sons, Inc., New York, Chapter 8.

[45] Yong, X. and William, S., 1994, "Variational calculation of the effective emissivity for a random bed", **International Journal of Heat and Mass Transfer**, Vol. 37, pp. 451-460.

[46] Edward, L.F. and Bradley, J.S., 2006, "Emissivity measurements of common construction materials", **In: Inframation 2006 proceeding**. Las Vegas, USA.

[47] Bouma, P.H. and de Goey, L.P.H., 1999, "Premixed combustion on ceramic foam burners", **Combustion and Flame**, Vol. 119, pp. 133–143.

[48] European Committee for Standardization, **Specification for gas heated catering equipment-Part 1: safety requirements**, EN 203-1:1992.

[49] European Committee for Standardization, **Specification for gas heated catering equipment-Part 2: safety requirements**, EN 203-1:1995.

[50] Dong, L.L., Leung, C.W. and Cheung, C.S., 2004, "Heat transfer and wall pressure characteristics of a twin premixed butane/air flame jets", **International Journal of Heat and Mass Transfer**, Vol. 47, pp. 489-500.

[51] Mishra, D.P., 2004, "Emission studies of impinging premixed flames", **Fuel**, Vol. 83, pp. 1743-1748.

[52] Zhen, H.S., Leung, C.W. and Cheung, C.S., 2011, "Combustion characteristics of a swirling inverse diffusion flame upon oxygen content variation", **Applied Energy**, Vol. 88, pp. 2925-2933.

[53] Dong, L.L., Cheung, C.S. and Leung, C.W., 2011, "Combustion optimization of a port-array inverse diffusion flame jet", **Energy**, Vol. 36, pp. 2834-2846.

[54] Pollution Control Department, **Air and noise quality standards** [Online], Available: http://www.pcd.go.th/info_serv/reg_std_airsnd03. html. [2011, July 29].

[55] Turns, S.R., 2000, **An introduction to combustion: concepts and applications**, 2nd ed., McGraw-Hill, Singapore, p. 513.

[56] Sathe, S.B., Kulkarni, H.R. and Tong, T.W., 1990, "An experimental and theoretical study of porous radiant burner performance", **The 23rd Symposium (International) on Combustion**, Pittsburgh, The combustion institute, pp. 1011-1018.

[57] Yoshizawa, Y., Echigo, R. and Tomimura, T., 1987, "A study on a high performance radiant heater", **Proceedings of the 2nd ASME/JSME Thermal Engineering Joint Conference**, Vol. 5, pp. 317-323.

[58] Oliveira, A.A.M. and Kaviany, M., 2001, "Nonequilibrium in the transport of heat and reactants in combustion in porous media", **Prog. Energy Combustion Science**, Vol. 27, pp. 523-545.

[59] Ashman, P.J., Junus, R., Stubington, J.F. and Sergeant, G.D., 1994, "The effects of load height on the emissions from a natural gas-fired domestic cooktop burner", **Combustion Science and Technology**, Vol. 103, pp.283-298.

[60] Jugjai, S. and Sanijai, S., 1996, "Parametric studies of thermal efficiency in a proposed porous radiant recirculated burner (PRRB): a design concept for the future burner", **RERIC International Energy Journal**, Vol. 18, pp. 97-111.

[61] Jugjai, S., 1995, "**High efficiency cooking stove**", Thai Patent, No. 8948.

[62] Reid, I.A.B., Robinson, C. and Smith, D.,B., 1984, "Spontaneous ignition of methane: measurement and chemical model", **The 23rd Symposium (International) on Combustion**, Pittsburgh, The combustion Institute, pp. 1833-1843.

[63] Yunus A.C., 2003, **Heat transfer a practical approach**, 2nd ed., McGraw-Hill, Singapore, p. 609.

APPENDIX A

Photograph of apparatus and flame shape

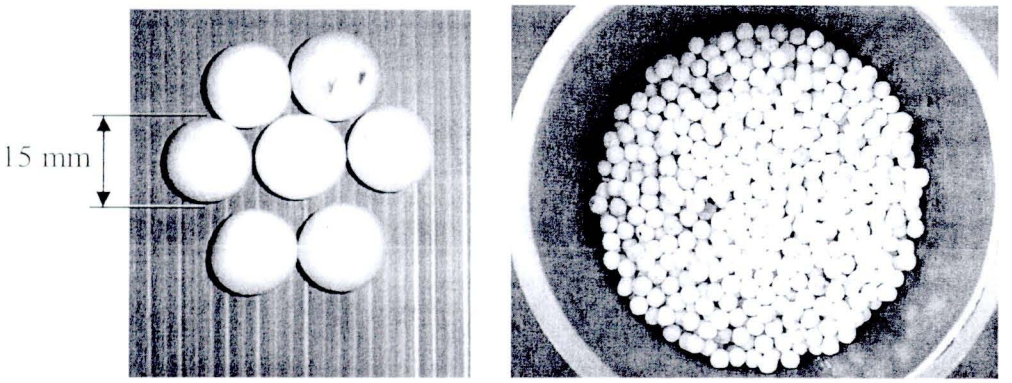


Figure A.1 Alumina spheres with particle diameter of d = 0.015 m (porous medium).

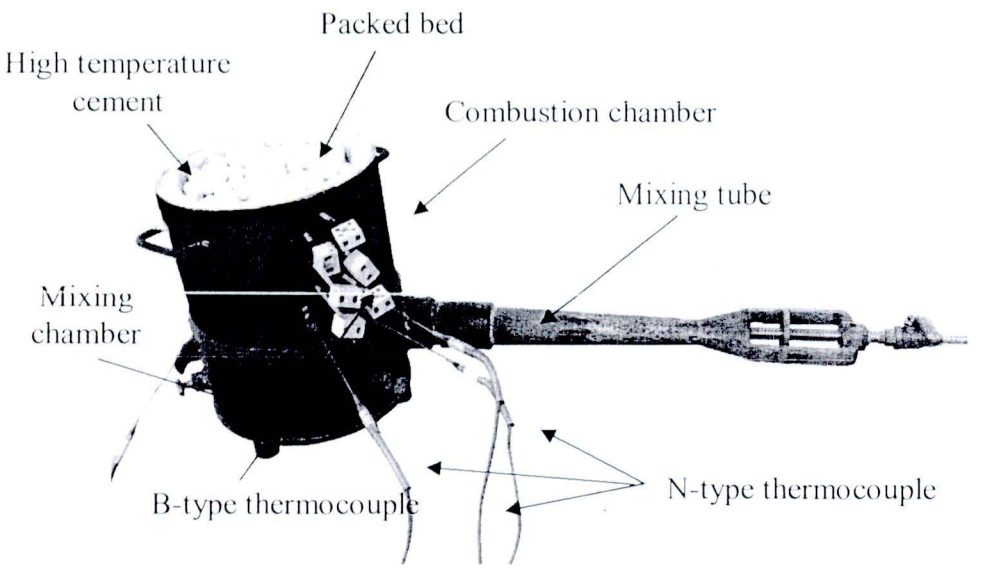


Figure A.2 SPMB with thermocouples.

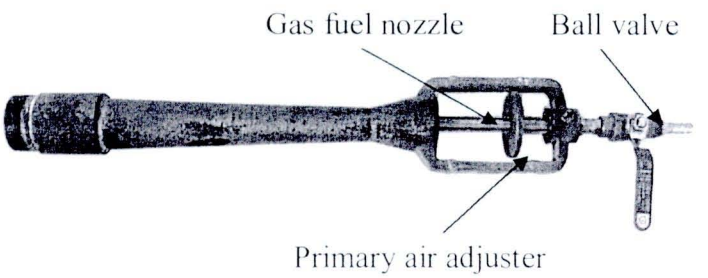


Figure A.3 Mixing tube of the SPMB in chapter 3.

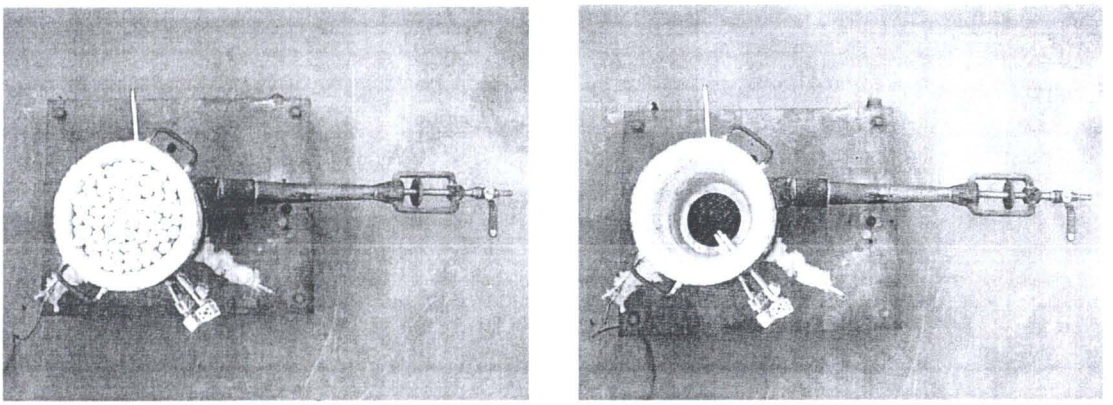


Figure A.4 SPMB with and without porous medium (top view).

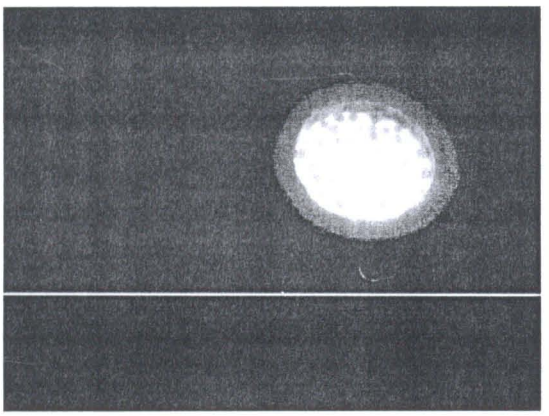


Figure A.5 Packed bed at shut down condition.

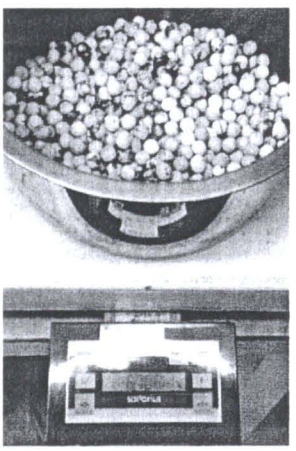


Figure A.6 Packed bed weight.

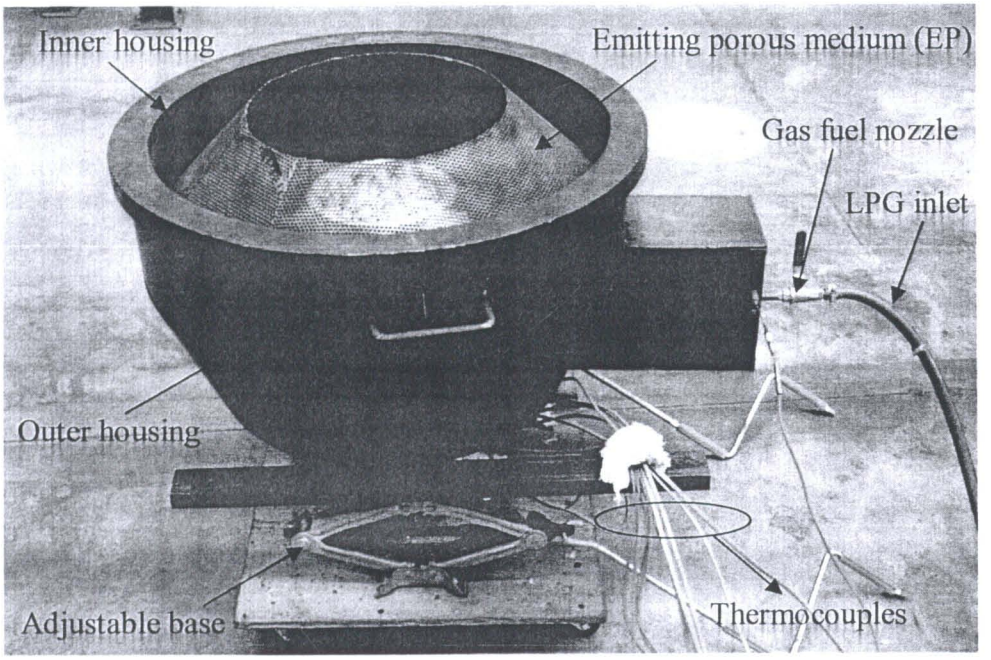


Figure A.7 SPMB with PRRB (side view).

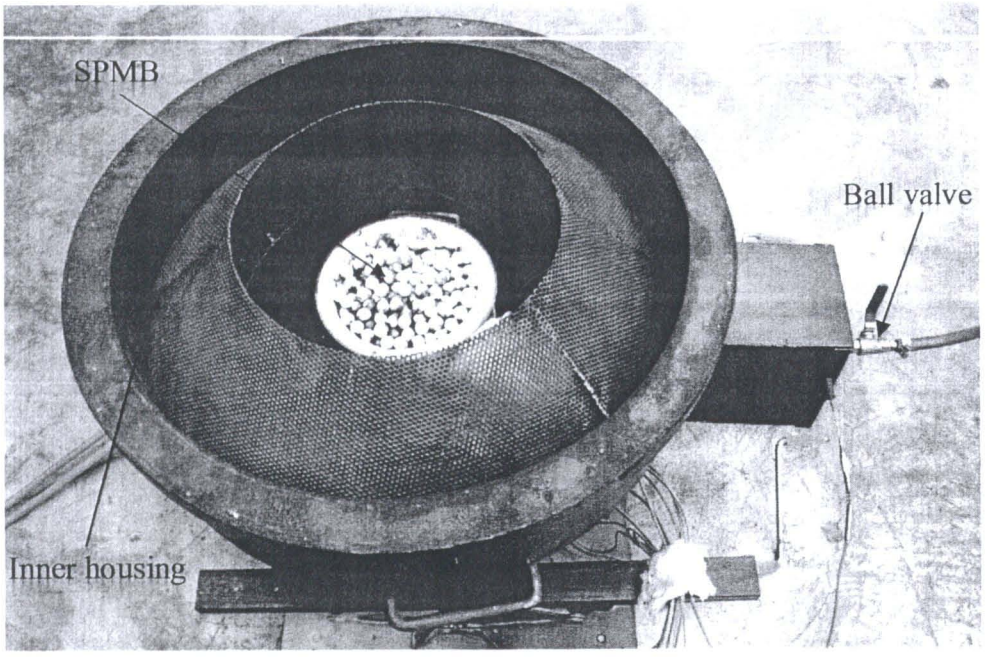


Figure A.8 SPMB with PRRB (top view).

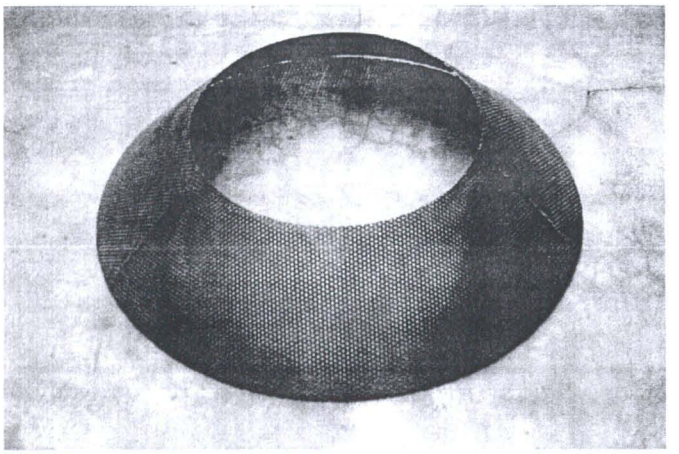


Figure A.9 Emitting porous medium (EP).

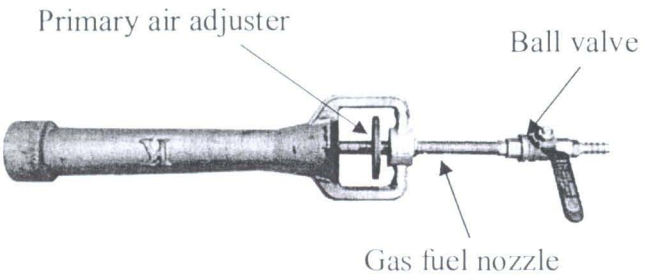


Figure A.10 Mixing tube of the SPMB and CB in chapters 4 and 5.

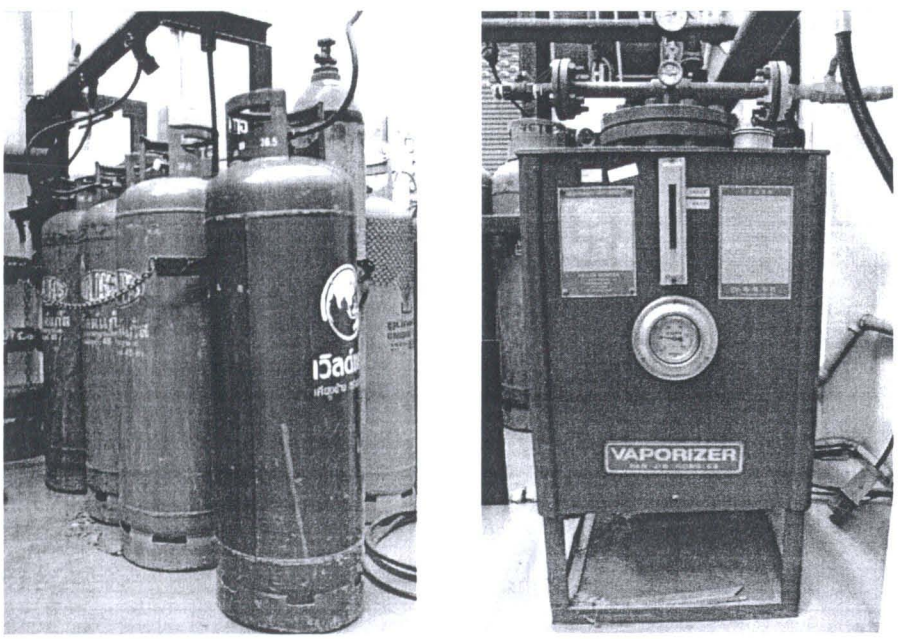


Figure A.11 LPG tanks and LPG vaporizer.

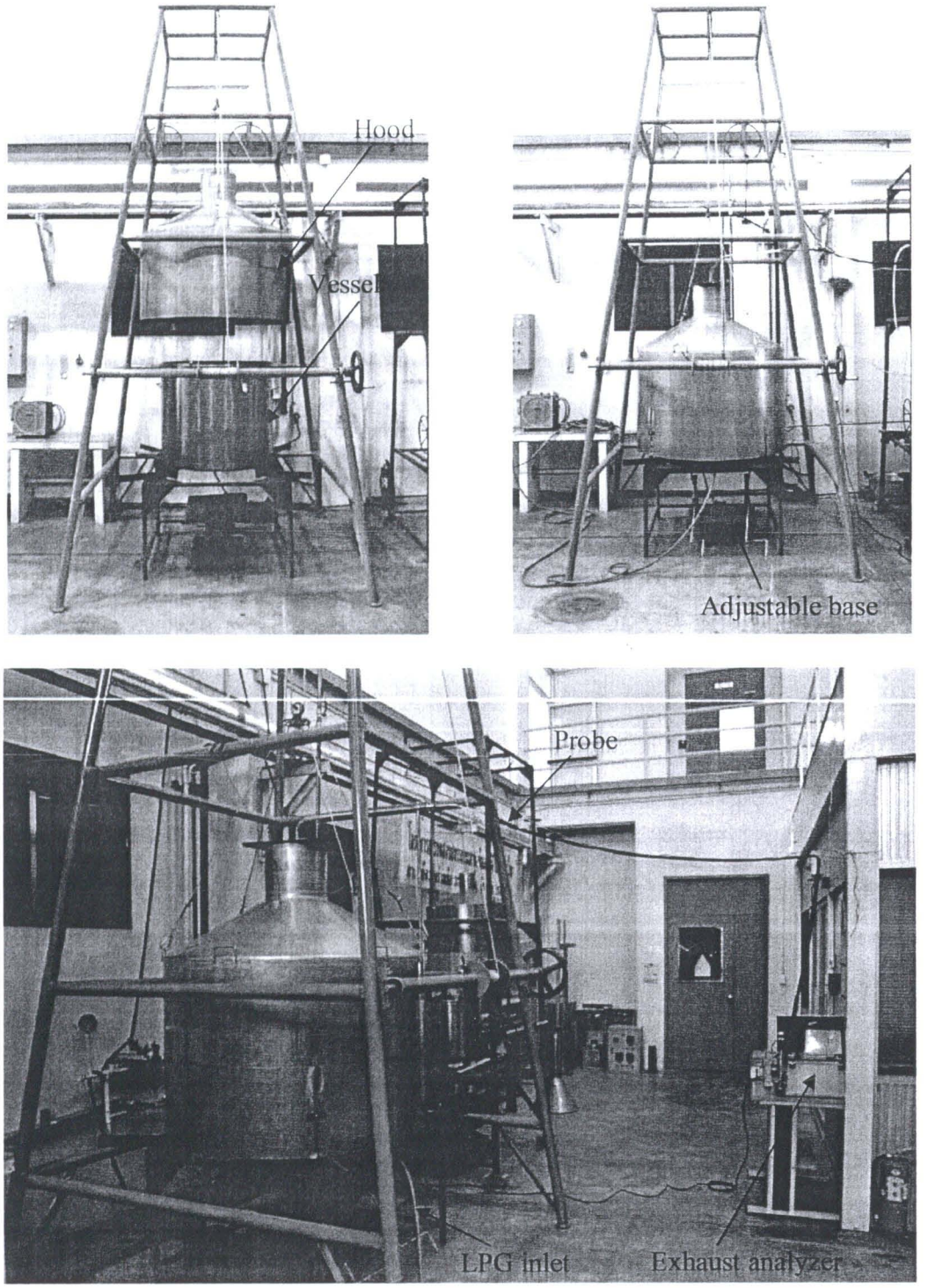


Figure A.12 Thermal performance platform.

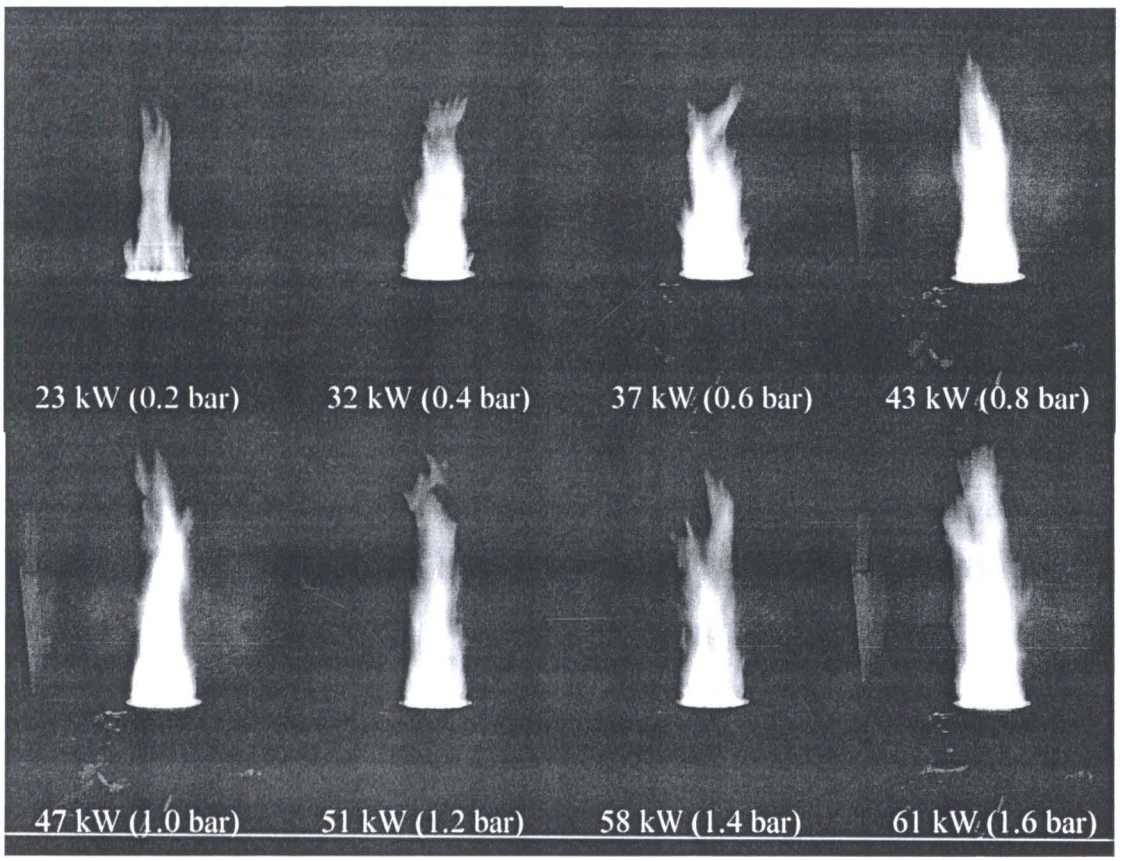


Figure A.13 Flame shape in SPMB at variation of *CL*.

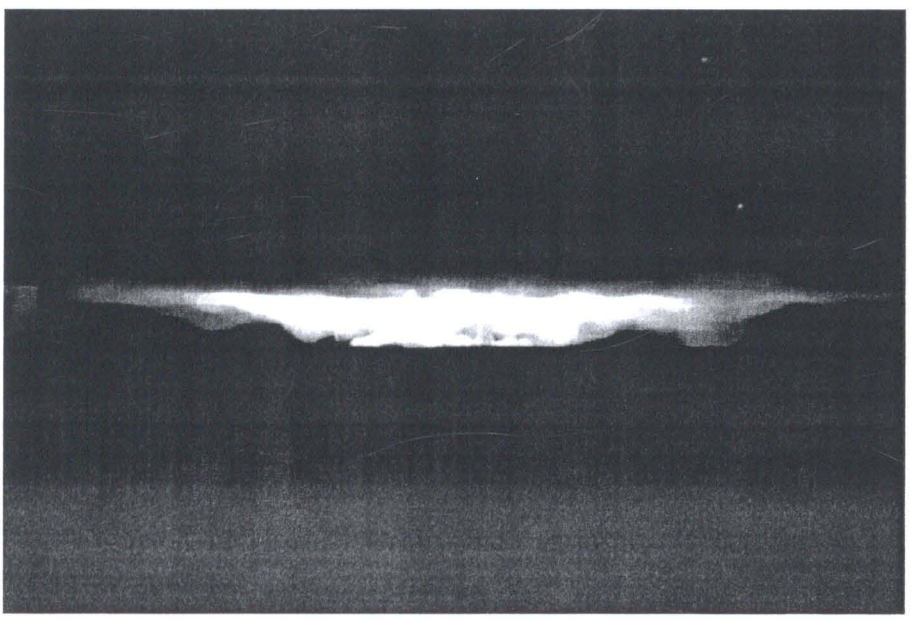


Figure A.14 Impingement flame of the SPMB at 34 kW and H =50 mm.

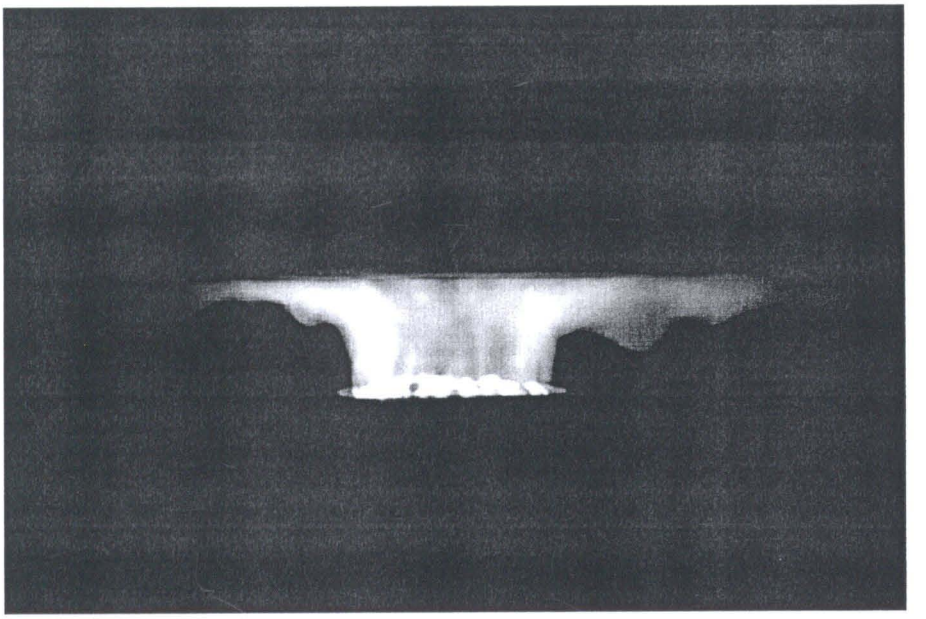


Figure A.15 Impingement flame of the SPMB at 44 kW and H =100 mm.

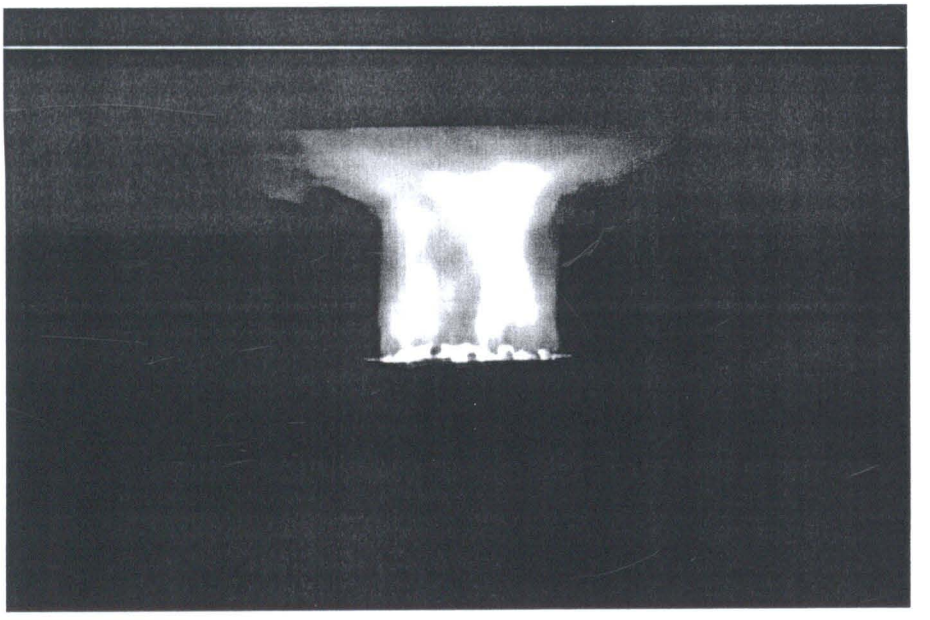


Figure A.16 Impingement flame of the SPMB at 44 kW and H =200 mm.

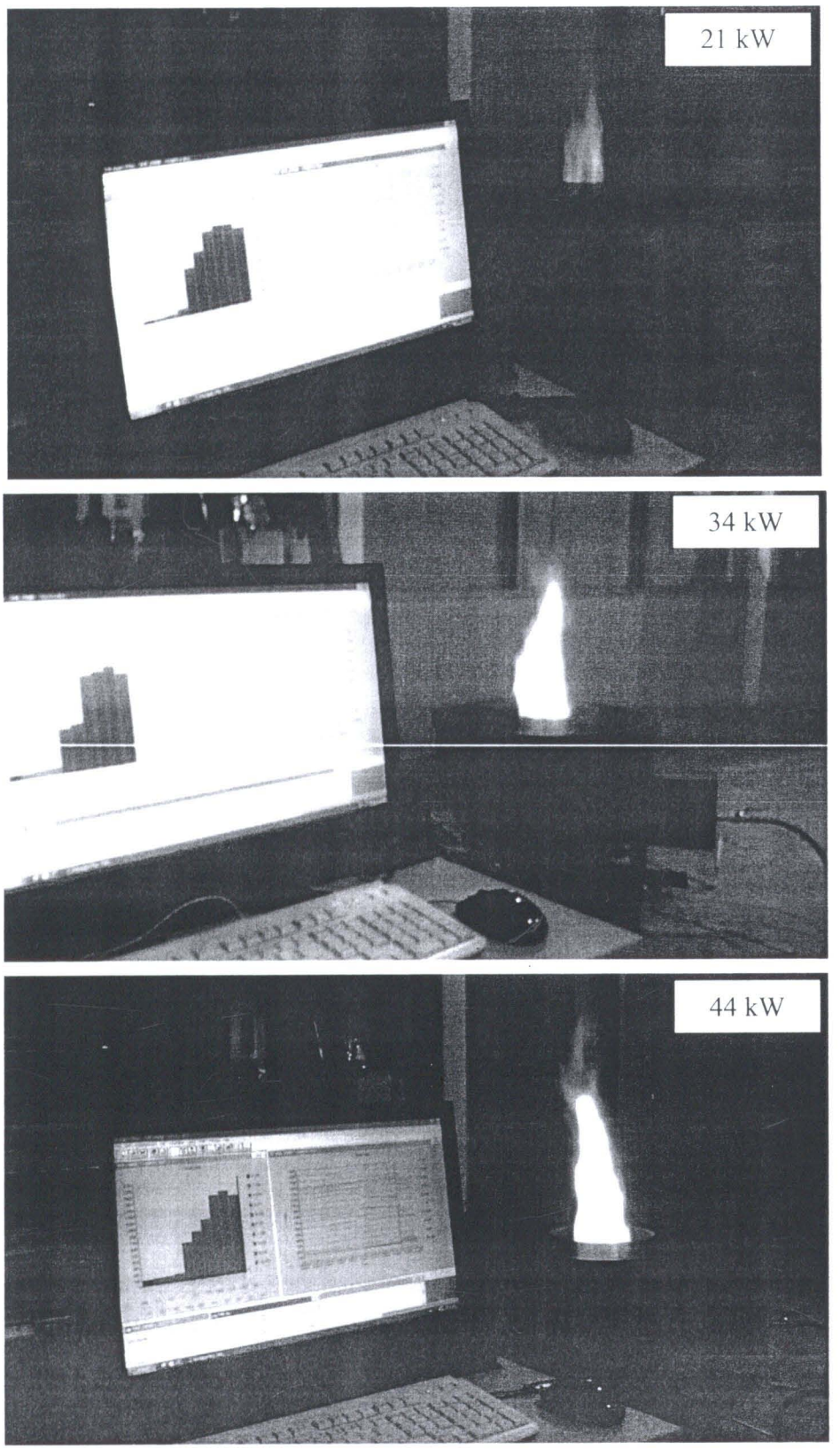


Figure A.17 Flame shape and temperature profile in packed bed of free flame of the SPMB with PRRB.

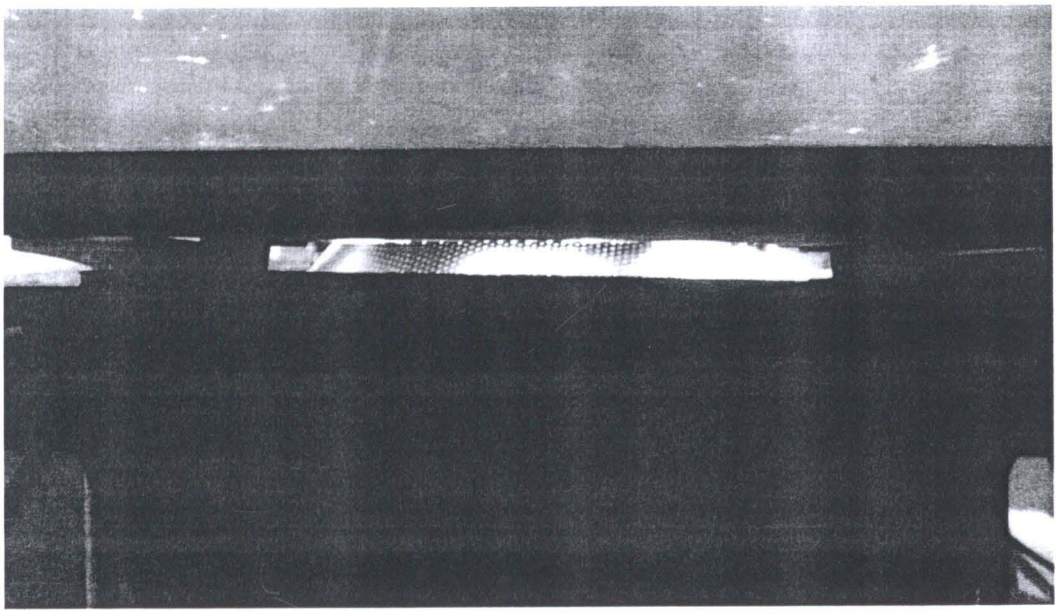


Figure A.18 Impingement flame of the SPMB with PRRB at 44 kW and H =125 mm.

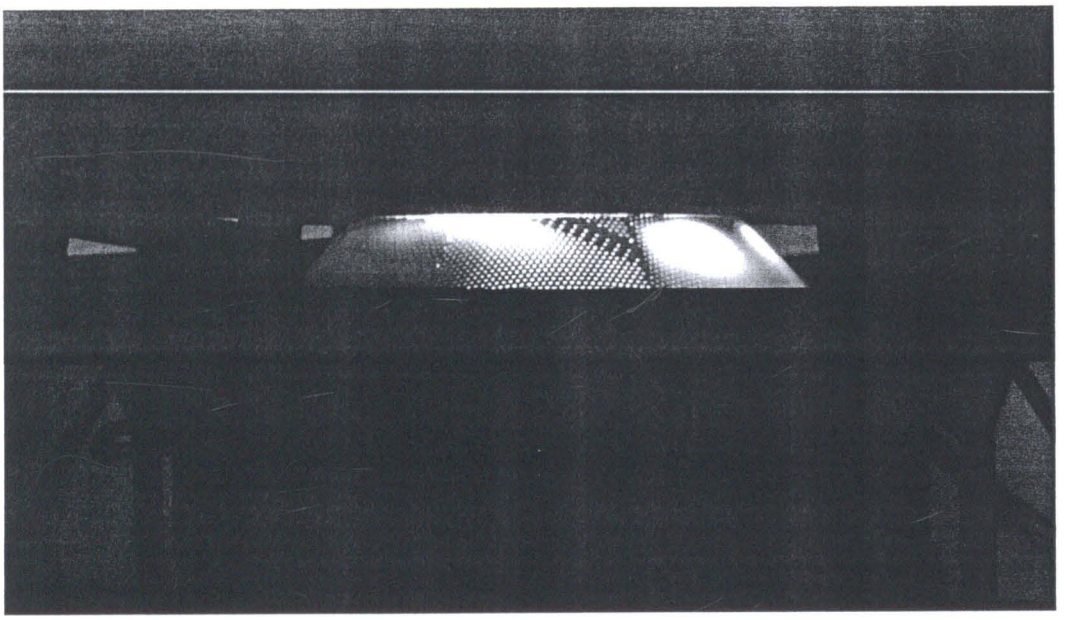


Figure A.19 Impingement flame of the SPMB with PRRB at 44 kW and H =200 mm.

APPENDIX B

Experimental data in graph

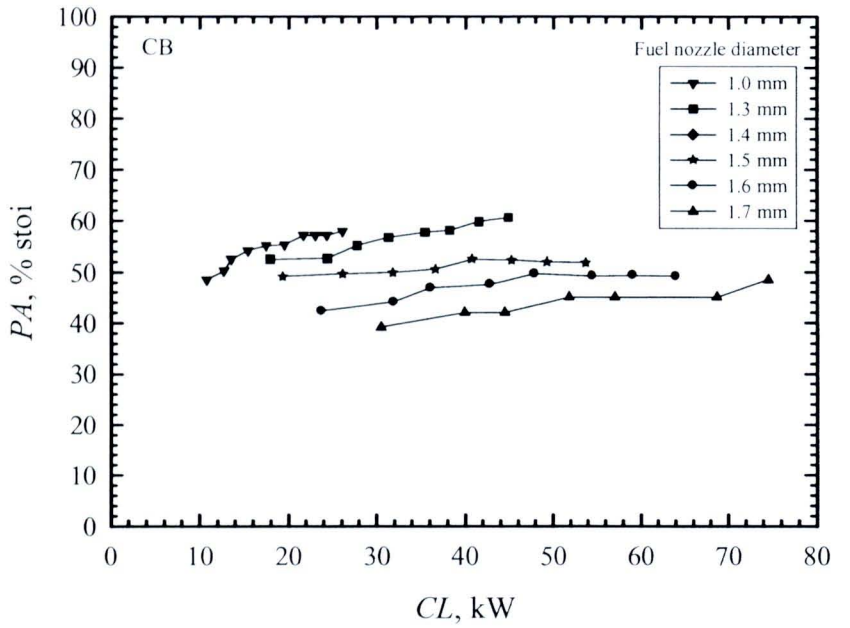


Figure B.1 Effect of gas fuel nozzle diameter on *PA* of the CB.

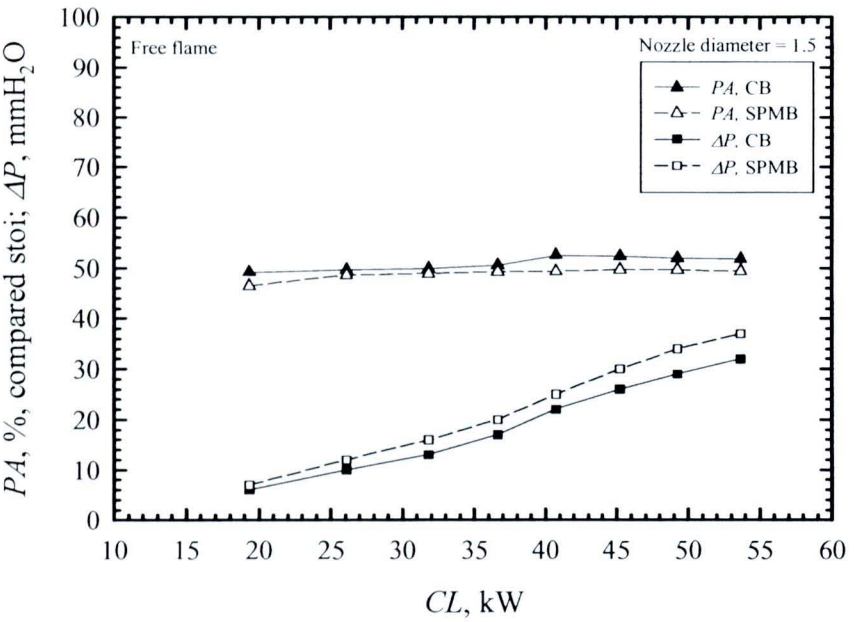


Figure B.2 Comparisons of *PA* and ΔP between the CB and SPMB.

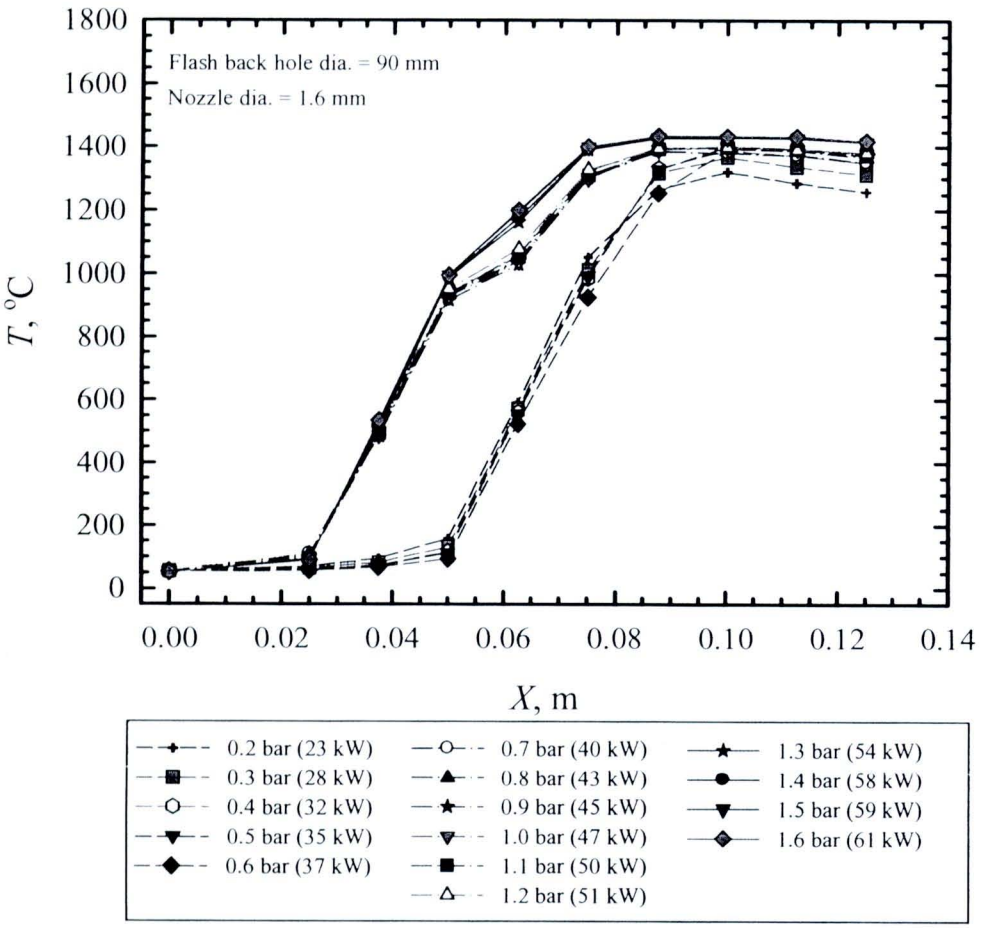


Figure B.3 Temperature profile within a packed bed of SPMB's free flame.

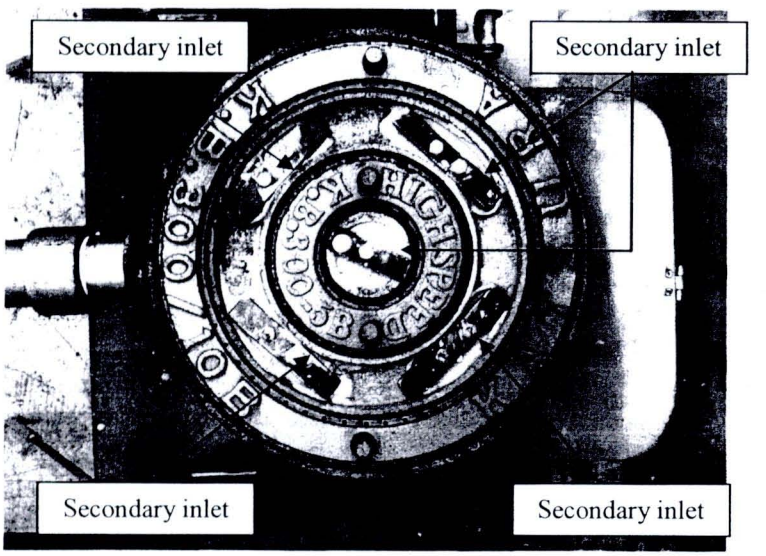


Figure B.4 CB without secondary air inlet.

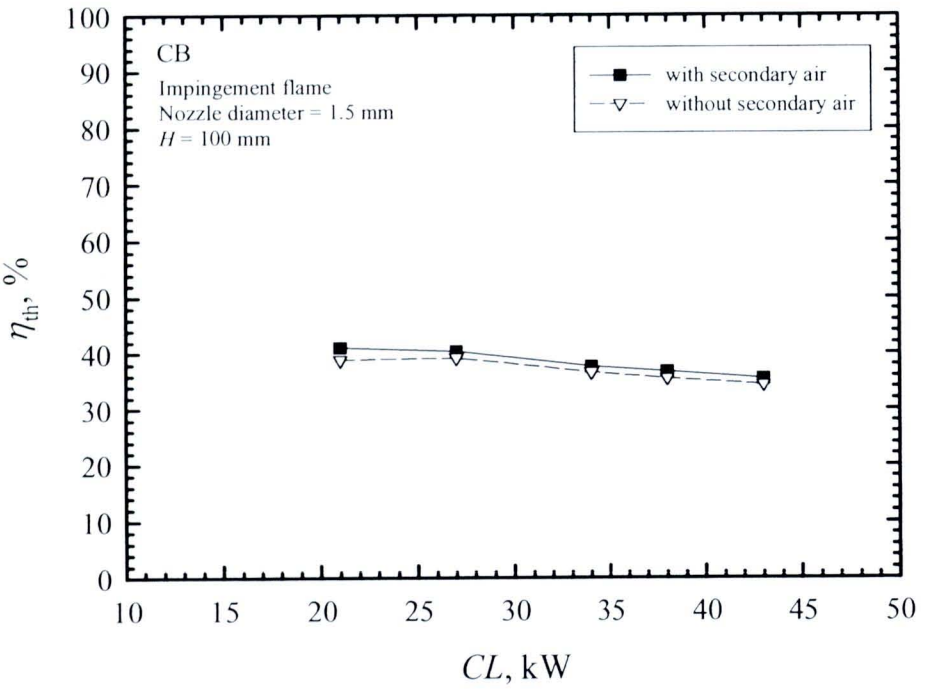


Figure B.5 Effect of secondary air on thermal efficiency of the CB.

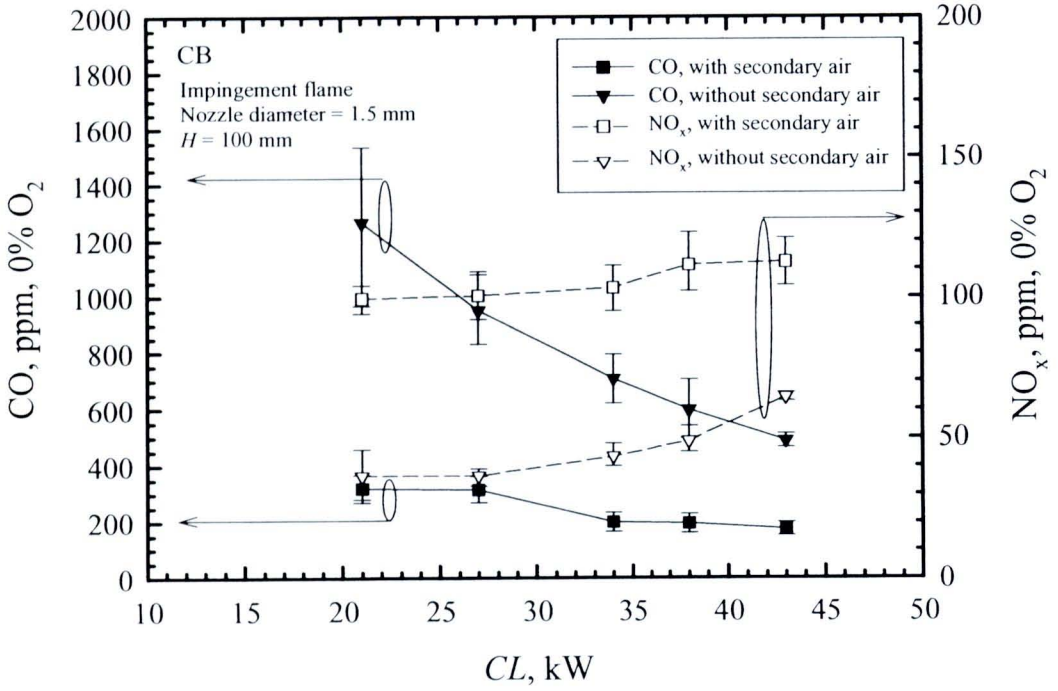


Figure B.6 Effect of secondary air on CO and NO_x emissions of the CB.

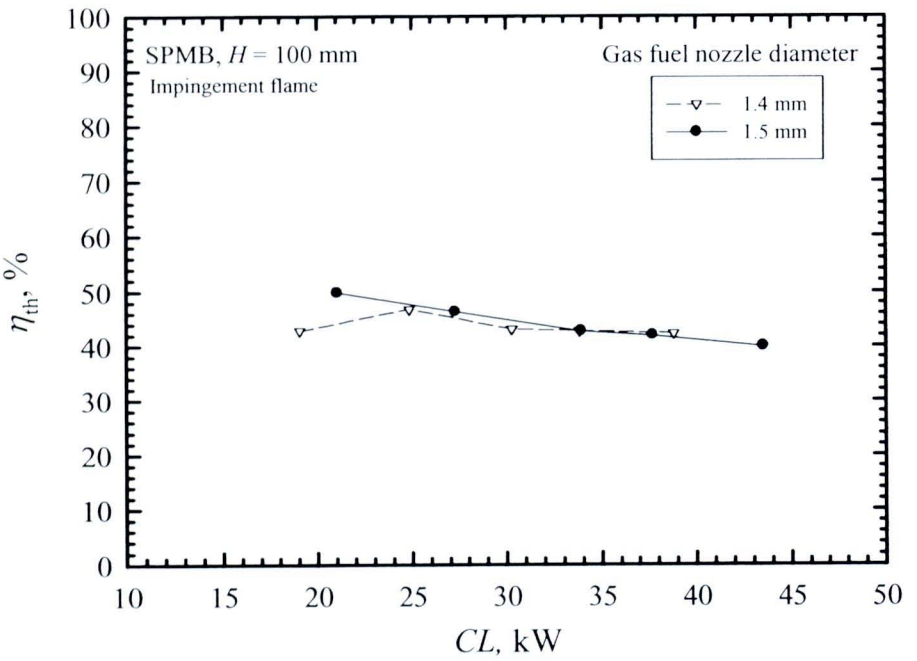


Figure B.7 Effect of nozzle diameter on thermal efficiency of the SPMB.

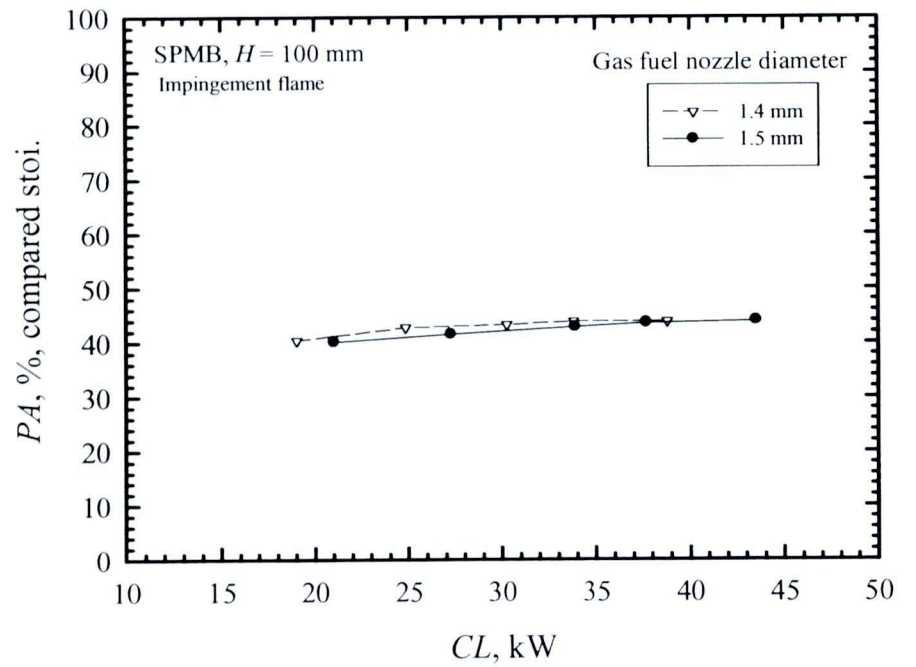


Figure B.8 Effect of nozzle diameter on PA of the SPMB.

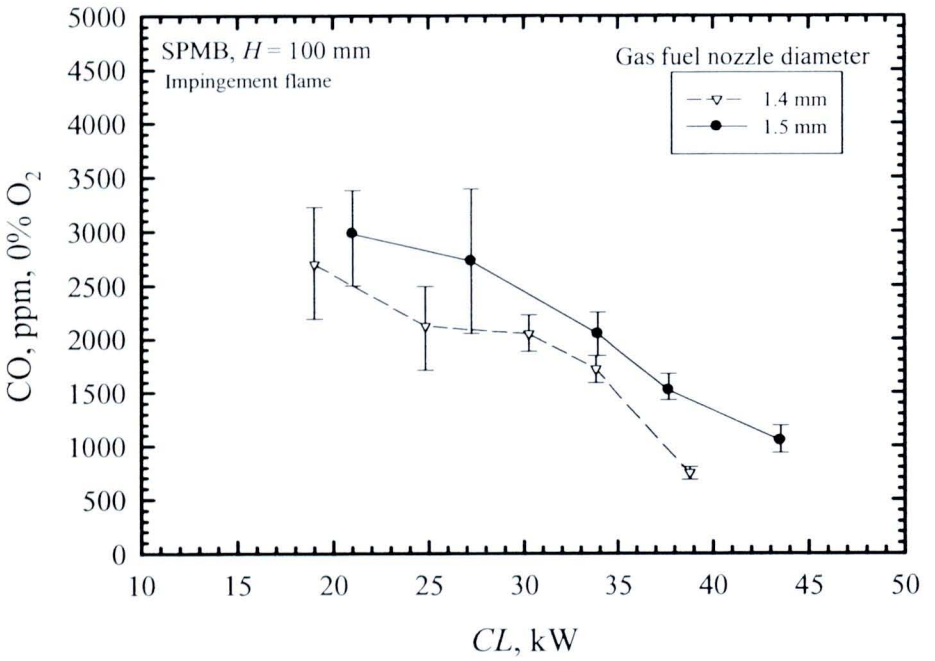


Figure B.9 Effect of nozzle diameter on CO emission of the SPMB.

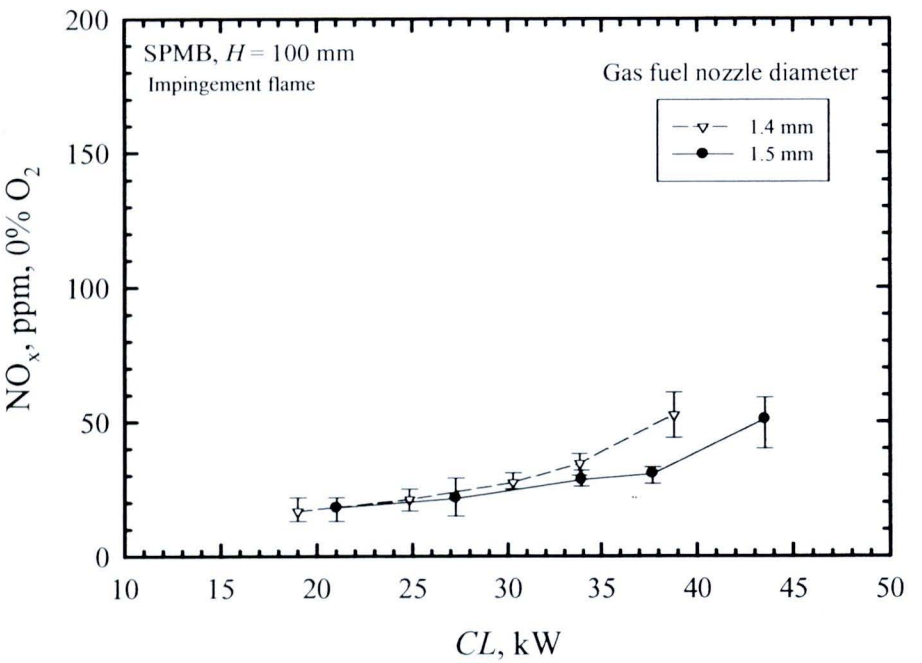


Figure B.10 Effect of nozzle diameter on NO_x emission of the SPMB.

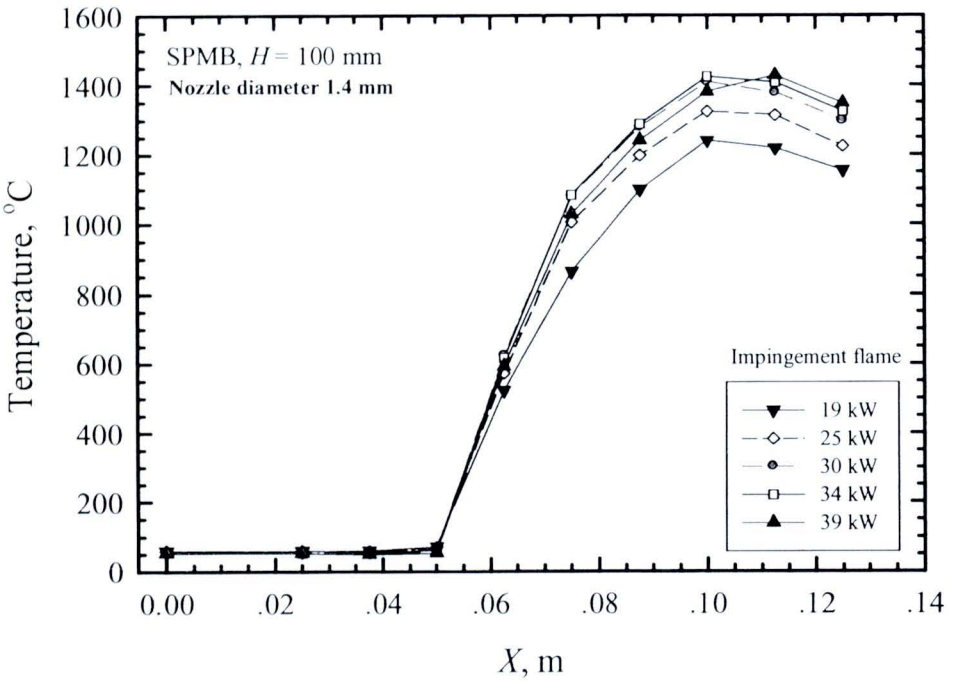


Figure B.11 The SPMB's temperature profile of nozzle diameter = 1.4 mm.

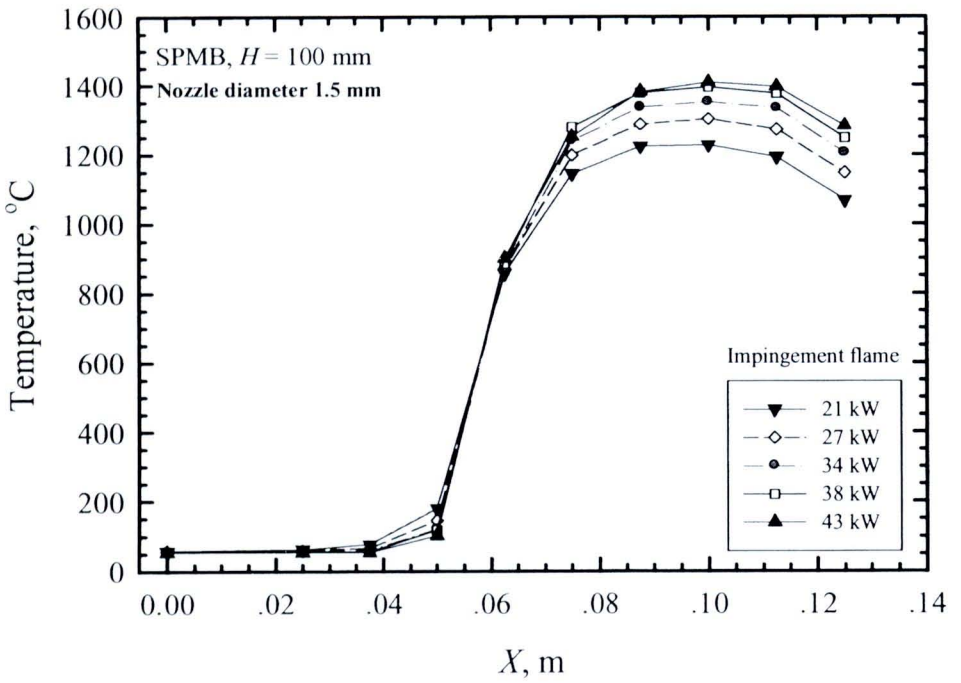


Figure B.12 The SPMB's temperature profile of nozzle diameter = 1.5 mm.

APPENDIX C

Experimental data in table

Table C.1 Effect of gas fuel nozzle diameter on *PA* of the CB.

Gas fuel nozzle diameter, mm	*CL*, kW	*PA*, %	ΔP, mmH_2O
1.0	10.77	48.53	2.5
	12.69	50.26	3
	13.54	52.53	4
	15.41	54.23	5
	17.44	55.16	6
	19.54	55.32	7.5
	21.67	57.20	8.5
	23.04	57.20	9
	24.36	57.20	10
	26.11	57.97	11
1.3	17.90	52.53	6
	24.41	52.68	9
	27.77	55.20	12
	31.31	56.74	15
	35.45	57.75	19
	38.23	58.14	22
	41.55	59.89	24
	44.86	60.63	26
1.5	19.33	49.22	6
	26.10	49.70	10
	31.81	49.96	13
	36.62	50.59	17
	40.73	52.53	22
	45.23	52.32	26
	49.24	52.00	29
	53.67	51.82	32
1.6	23.74	42.36	9
	31.91	44.14	13
	36.07	46.88	17
	42.78	47.56	23
	47.88	49.67	27
	54.47	49.22	32
	59.05	49.38	36
	63.99	49.16	38
1.7	30.48	39.21	8
	39.91	42.03	14
	44.45	42.03	18
	51.81	45.06	21
	57.03	45.06	25
	68.66	45.06	34
	74.52	48.53	38

Table C.2 Comparisons of PA and ΔP between the CB and SPMB.

Gas fuel nozzle diameter, mm	CL, kW	PA, %	ΔP, mmH_2O
1.5 (CB)	19.33	49.22	6
	26.10	49.70	10
	31.81	49.96	13
	36.62	50.59	17
	40.73	52.53	22
	45.23	52.32	26
	49.24	52.00	29
	53.67	51.82	32
1.5 (SPMB)	19.33	46.54	7
	26.10	48.59	12
	31.81	48.91	16
	36.62	49.25	20
	40.73	49.32	25
	45.23	49.64	30
	49.24	49.61	34
	53.67	49.35	37

Table C.3 Temperature profile within a packed bed of SPMB's free flame.

X, m	CL, kW							
	23	28	32	35	37	40	43	45
	Temperature, °C							
0	55	56	55	56	55	56	56	56
0.025	70	65	59	59	57	109	108	102
0.0375	95	83	76	73	68	512	501	483
0.05	158	133	117	112	95	935	937	916
0.0625	591	572	560	554	523	1,044	1,059	1,029
0.075	1,052	1,012	985	993	925	1,305	1,323	1,303
0.0875	1,265	1,317	1,332	1,326	1,253	1,385	1,397	1,395
0.1	1,321	1,366	1,388	1,402	1,394	1,380	1,394	1,400
0.1125	1,285	1,336	1,371	1,391	1,391	1,373	1,387	1,395
0.125	1,258	1,312	1,349	1,371	1,379	1,350	1,367	1,377

Table C.3 (cont.) Temperature profile within a packed bed of SPMB's free flame.

X, m	CL, kW						
	47	50	51	54	58	59	61
	Temperature, °C						
0	55	55	54	52	52	53	52
0.025	97	96	94	97	95	95	91
0.0375	487	494	503	505	517	526	534
0.05	926	938	953	986	987	996	996
0.0625	1,038	1,055	1,077	1,161	1,176	1,194	1,198
0.075	1,299	1,310	1,327	1,390	1,390	1,399	1,400
0.0875	1,390	1,392	1,395	1,429	1,427	1,431	1,435
0.1	1,398	1,398	1,398	1,432	1,427	1,428	1,434
0.1125	1,393	1,393	1,391	1,435	1,428	1,427	1,432
0.125	1,379	1,381	1,381	1,418	1,415	1,415	1,418

Table C.4 Effect of secondary air on thermal performance of the CB at H = 100 mm.

Burner	CL, kW	η_{th}, %	CO, ppm, 0% O_2			NO_x, ppm, 0% O_2			PA, %
			avg.	min.	max.	avg.	min.	max.	
CB with secondary air	21	41.05	369	270	539	100	94	104	47.38
	27	40.38	363	269	494	101	92	108	48.29
	34	37.60	233	164	343	103	95	111	49.32
	38	36.75	228	160	317	109	102	123	50.00
	43	35.43	199	151	245	112	104	121	51.24
CB without secondary air	21	38.87	1,291	968	1,535	36	28	46	46.71
	27	39.18	931	830	1,091	37	33	39	48.32
	34	36.55	706	621	795	42	40	48	49.06
	38	35.51	590	497	705	47	45	54	50.03
	43	34.36	487	465	514	64	63	66	50.86

Table C.5 Effect of nozzle diameter on thermal performance of the SPMB.

Nozzle diameter, mm	*CL*, kW	η_{th}, %	CO, ppm, 0% O_2			NO_x, ppm, 0% O_2			*PA*, %	ΔP, mmH_2O
			avg.	min.	max.	avg.	min.	max.		
1.4 (*H* = 100 mm)	19	42.80	2,675	2,191	3,228	15	13	22	40.43	7
	25	46.77	2,154	1,711	2,490	21	17	25	42.73	10
	30	43.09	2,029	1,881	2,224	26	25	31	43.25	15
	34	42.77	1,713	1,592	1,844	35	30	38	43.83	18
	39	42.31	749	682	805	53	44	61	43.85	21
1.5 (*H* = 100 mm)	21	49.79	3,055	2,501	3,379	19	13	22	40.1	8
	27	46.31	2,729	2,049	3,392	20	15	29	41.5	12
	34	42.73	2,037	1,844	2,250	27	26	32	42.8	19
	38	41.94	1,456	1,431	1,672	32	27	33	43.5	25
	43	39.91	1,019	934	1,190	54	40	59	43.9	31

Table C.6 Temperature of SPMB at *H* = 100 mm and nozzle diameter = 1.4 mm.

	Nozzle diameter = 1.4 mm				
X, m	*CL*, kW				
	19	25	30	34	39
	Temperature, °C				
0	60	59	57	55	54
0.025	59	58	56	54	53
0.0375	59	58	57	54	50
0.05	72	69	65	60	54
0.0625	523	572	623	615	593
0.075	865	1,006	1,080	1,084	1,028
0.0875	1,099	1,197	1,277	1,288	1,240
0.1	1,240	1,325	1,409	1,424	1,382
0.1125	1,218	1,314	1,378	1,409	1,429
0.125	1,154	1,224	1,298	1,325	1,349

Table C.7 Temperature of SPMB at H = 100 mm and nozzle diameter = 1.5 mm.

X, m	Nozzle diameter = 1.5 mm				
	CL, kW				
	21	27	34	38	43
	Temperature, °C				
0	59	57	56	54	53
0.025	63	59	56	55	54
0.0375	77	66	60	57	53
0.05	180	146	121	117	101
0.0625	857	872	871	885	902
0.075	1,145	1,198	1,239	1,278	1,252
0.0875	1,223	1,287	1,337	1,379	1,383
0.1	1,227	1,302	1,353	1,395	1,410
0.1125	1,193	1,272	1,334	1,376	1,397
0.125	1,068	1,148	1,204	1,248	1,282

Table C.8 Temperature in packed bed of the SPMB at CL = 21 kW.

X, m	CL = 21 kW, Nozzle diameter = 1.5 mm					
	H, mm					
	50	75	100	125	150	175
	Temperature, °C					
0	67	63	60	58	55	54
0.025	81	74	63	61	58	56
0.0375	139	123	67	63	59	57
0.05	217	173	133	119	100	91
0.0625	813	741	670	644	608	599
0.075	1,162	1,044	981	937	879	821
0.0875	1,265	1,213	1,153	1,106	1,043	1,003
0.1	1,265	1,260	1,256	1,254	1,231	1,213
0.1125	1,239	1,248	1,248	1,241	1,242	1,249
0.125	1,128	1,130	1,144	1,150	1,159	1,161

Table C.9 Temperature in packed bed of the SPMB at CL = 34 kW.

	CL = 34 kW, Nozzle diameter = 1.5 mm					
	H, mm					
X, m	50	75	100	125	150	175
	Temperature, °C					
0	57	55	52	51	50	49
0.025	57	55	52	51	50	49
0.0375	63	60	56	56	55	53
0.05	74	68	64	66	64	62
0.0625	645	602	587	627	611	584
0.075	1,036	999	984	1,021	1,006	986
0.0875	1,261	1,227	1,213	1,246	1,233	1,217
0.1	1,360	1,328	1,314	1,347	1,334	1,320
0.1125	1,367	1,359	1,353	1,366	1,362	1,352
0.125	1,312	1,311	1,306	1,315	1,313	1,305

Table C.10 Temperature in packed bed of the SPMB at CL = 44 kW.

	CL = 44 kW, Nozzle diameter = 1.5 mm					
	H, mm					
X, m	50	75	100	125	150	175
	Temperature, °C					
0	56	54	54	52	50	48
0.025	55	54	53	52	49	47
0.0375	59	57	56	54	53	51
0.05	67	64	64	62	62	60
0.0625	698	671	676	682	722	735
0.075	1,086	1,055	1,061	1,068	1,146	1,157
0.0875	1,395	1,369	1,367	1,366	1,382	1,382
0.1	1,436	1,417	1,414	1,413	1,401	1,401
0.1125	1,430	1,424	1,423	1,421	1,420	1,421
0.125	1,364	1,359	1,365	1,362	1,368	1,368

Table C.11 Combustion performance of the CB.

Burner	H, mm	CL, kW	η_{th}, %	CO, ppm, 0% O_2			NO_x, ppm, 0% O_2			PA, %	ΔP, mmH_2O
				avg.	min.	max.	avg.	min.	max.		
CB	50	21	49.70	1,148	856	1,424	43	38	46	42.42	8
		27	49.51	1,123	883	1,511	43	31	50	42.43	12
		34	45.89	1,025	673	1,164	44	38	57	42.46	19
		38	45.70	942	865	999	47	44	57	42.48	22
		44	45.58	813	692	943	64	56	71	43.38	26
	75	21	45.80	540	465	677	60	51	66	46.94	7
		27	42.05	476	373	615	61	51	70	47.59	12
		34	40.97	399	313	578	63	54	74	48.32	17
		38	39.51	344	237	549	67	62	73	48.50	21
		44	39.42	335	292	395	83	77	91	48.59	25
	100	21	41.05	369	270	539	100	94	104	47.38	7
		27	40.38	363	269	494	101	92	108	48.29	11
		34	37.60	233	164	343	103	95	111	49.32	17
		38	36.75	228	160	317	109	102	123	50.00	22
		44	34.36	199	151	245	112	104	121	51.24	25
	125	21	36.41	134	72	224	104	94	111	49.35	7
		27	34.11	135	87	209	107	98	119	50.37	11
		34	33.93	182	98	231	109	100	118	50.52	17
		38	33.73	289	160	545	114	107	127	50.69	22
		44	33.64	403	313	470	115	108	124	51.65	26

Table C.12 Combustion performance of the SPMB.

Burner	H, mm	CL, kW	η_{th}, %	CO, ppm, 0% O_2			NO_x, ppm, 0% O_2			PA, %	ΔP, mmH_2O
				avg.	min.	max.	avg.	min.	max.		
SPMB	50	21	57.64	6,221	5,817	6,703	10	10	11	40.12	8
		27	50.59	5,013	4,726	5,329	13	11	14	41.25	15
		34	43.55	3,805	3,635	3,954	16	12	17	42.39	22
		38	42.13	3,304	3,169	3,448	22	19	24	42.78	27
		44	40.72	2,803	2,703	2,941	27	25	30	43.17	32
	75	21	52.88	4,443	4,110	4,954	12	12	18	40.36	8
		27	47.57	4,011	3,598	4,552	15	10	15	41.96	12
		34	44.63	2,837	2,347	3,178	24	22	31	42.63	19
		38	43.17	2,258	1,955	2,465	24	21	32	43.30	25
		44	42.92	1,753	1,003	1,909	37	29	45	43.42	31
	100	21	49.79	3,055	2,501	3,379	14	13	22	40.12	8
		27	46.31	2,729	2,049	3,392	20	15	29	41.47	12
		34	42.73	2,037	1,844	2,250	27	26	32	42.78	19
		38	41.94	1,456	1,431	1,672	32	27	33	43.52	25
		44	39.91	1,019	934	1,190	54	40	59	43.91	31
	125	21	46.03	2,557	2,194	3,070	19	13	22	41.03	8
		27	43.44	1,824	1,558	2,187	22	20	31	41.92	12.5
		34	40.85	1,090	922	1,304	30	26	39	42.80	17
		38	39.24	944	786	1,151	44	36	51	43.77	24
		44	37.63	797	650	997	58	46	63	44.74	31
	150	21	42.04	2,107	1,780	2,454	18	14	24	41.49	8
		27	40.81	1,508	1,260	1,764	26	21	30	42.40	12.5
		34	39.58	908	740	1,074	34	28	35	43.32	17
		38	38.24	816	707	1,234	49	43	52	44.03	24
		44	36.90	724	674	1,393	64	57	68	44.74	31
	175	21	41.07	1,816	1,471	2,186	19	16	25	42.03	8
		27	39.37	1,281	1,080	1,869	32	26	37	42.87	12.5
		34	37.68	746	688	1,552	46	36	49	43.71	17
		38	36.56	708	647	1,134	55	47	59	44.24	24
		44	35.43	670	606	716	64	57	68	44.77	31

Table C.13 Temperature in packed bed of the SPMB with PRRB at CL = 21 kW.

	CL = 21 kW, Nozzle diameter = 1.5 mm		
X, m	H, mm		
	125	175	200
	Temperature, °C		
0	170	156	152
0.025	159	152	146
0.0375	173	162	151
0.05	176	165	153
0.0625	415	398	380
0.075	513	589	646
0.0875	780	846	912
0.1	1,094	1,140	1,185
0.1125	1,170	1,213	1,257
0.125	1,068	1,117	1,164

Table C.14 Temperature in packed bed of the SPMB with PRRB at CL = 34 kW.

	CL = 34 kW, Nozzle diameter = 1.5 mm		
X, m	H, mm		
	125	175	200
	Temperature, °C		
0	209	196	189
0.025	202	187	184
0.0375	203	188	182
0.05	208	192	185
0.0625	373	321	270
0.075	457	512	596
0.0875	902	960	1,018
0.1	1,128	1,200	1,273
0.1125	1,212	1,291	1,369
0.125	1,143	1,212	1,250

Table C.15 Temperature in packed bed of the SPMB with PRRB at CL = 44 kW.

	CL = 44 kW, Nozzle diameter = 1.5 mm		
X, m	H, mm		
	125	175	200
	Temperature, °C		
0	234	215	210
0.025	230	211	187
0.0375	231	211	190
0.05	233	208	179
0.0625	455	414	381
0.075	551	606	685
0.0875	983	1,045	1,181
0.1	1,157	1,229	1,315
0.1125	1,255	1,307	1,399
0.125	1,192	1,266	1,315

Table C.16 Combustion performance of the SPMB with PRRB.

Burner	H, mm	CL, kW	η_{th}, %	CO, ppm, 0% O_2			NO_x, ppm, 0% O_2			PA, %	ΔP, mmH_2O
				avg.	min.	max.	avg.	min.	max.		
SPMB with PRRB	125	21	52.85	15,149	11,412	20,243	16	13	20	39.35	9
		34	51.48	10,265	7,617	13,097	14	13	17	39.80	19
		44	51.28	7,513	5,765	10,309	16	13	17	40.74	29
	175	21	50.65	8,539	7,469	9,601	13	12	19	39.46	9
		34	50.07	5,968	5,311	6,362	31	22	35	39.82	19
		44	49.96	5,196	4,915	5,594	78	72	86	40.96	29
	200	21	48.84	7,662	7,073	8,183	19	13	21	39.56	8
		34	46.13	5,334	4,944	5,771	35	31	41	39.97	19
		44	46.04	4,163	3,829	4,646	78	75	87	41.33	29

Table C.17 Comparison of thermal efficiency.

Burner	H, mm	CL, kW	η_{th}, %
CB in Ref.[6]	63.5	33	28.53
		35	29.61
		40	30.96
		44	32.11
		48	33.77
		50	35.59
		52	35.83
		58	35.17
		63	34.70
		69	32.41
PRRB[SB] in Ref.[6]	127	33	35.49
		35	36.95
		40	38.65
		44	40.12
		48	42.26
		50	44.02
		52	44.27
		58	41.70
		63	39.31
		69	36.62
SPMB	125	21	46.03
		27	43.44
		34	40.85
		38	39.24
		44	37.63
SPMB with PRRB	125	21	52.85
		34	51.48
		44	51.28

Table C.18 Output radiation efficiency and radiative heat loss of free flame.

CL, kW	$\eta_{\text{rad,loss}}$, %	η_{rad}, %	$q_r^n(0)$, W/m^2	$q_r^n(\tau_E)$, W/m^2
23.26	0.1992	22.1148	2,621.44	291,029.25
28.37	0.1613	21.0402	2,589.58	337,742.43
32.46	0.1417	20.3248	2,603.28	373,287.93
35.27	0.1280	19.8030	2,553.87	395,205.04
37.31	0.1142	19.3626	2,410.20	408,817.42
40.38	0.3029	16.3802	6,920.84	374,274.47
42.68	0.2891	16.2486	6,981.27	392,413.86
44.98	0.2597	15.8959	6,610.44	404,586.60
46.77	0.2522	15.4966	6,673.61	410,110.86
49.58	0.2440	14.7999	6,846.62	415,215.91
51.37	0.2436	14.3443	7,081.78	416,955.22
53.92	0.2556	14.6775	7,798.89	447,866.19
57.50	0.2435	13.7603	7,922.43	447,736.44
59.30	0.2422	13.4028	8,128.28	449,785.54
61.08	0.2368	13.0851	8,183.27	452,260.64

APPENDIX D

Contribution of heat transfer of the SPMB and SPMB with PRRB

From the results of thermal efficiency of the SPMB and SPMB with PRRB that had high thermal efficiency when compare with the CB. Due to an enhancement of radiative heat transfer and heat recirculation from the porous medium technology. Figure D.1 shows a simplified model for thermal efficiency contribution of the CB, SPMB and SPMB with PRRB. Main heat transfer mode of the CB is a convective heat transfer mode because a physical phenomena of CB's flame is a directly impinging flame. So the thermal efficiency of the CB is only the convective thermal efficiency that is calculated by Eq. (4.1).

The SPMB's flame has two parts:- (1) the main flame is a matrix-stabilized flame within the packed bed and (2) a post flame that is over a burner top and it impinge the vessel bottom. So the thermal efficiency of the SPMB consists of convective and radiative thermal efficiencies. But the SPMB with PRRB has more thermal efficiency component than one because it has a heat recirculated unit. Therefore the contribution of thermal efficiency of all burners can be characterized in three components:- the convective thermal efficiency ($\eta_{th,conv}$), the radiative thermal efficiency ($\eta_{th,rad}$), and the recirculated thermal efficiency ($\eta_{th,recir}$) as shown in Eq. (D.1).

$$\eta_{th} = \eta_{th,conv} + \eta_{th,rad} + \eta_{th,recir} \tag{D.1}$$

The radiative thermal efficiency, $\eta_{th,rad}$, is a function of output radiation at exit of packed bed and view factor from burner output and vessel bottom. Eq. (D.2) use to calculate the $\eta_{th,rad}$. Methodology of calculation for output radiation at packed bed exit, $q^n(\tau_E)$, is shown in section 3.3.6 and view factor, $F_{i\to j}$, can be estimated by Eqs. (D.3 - D.5) [63],

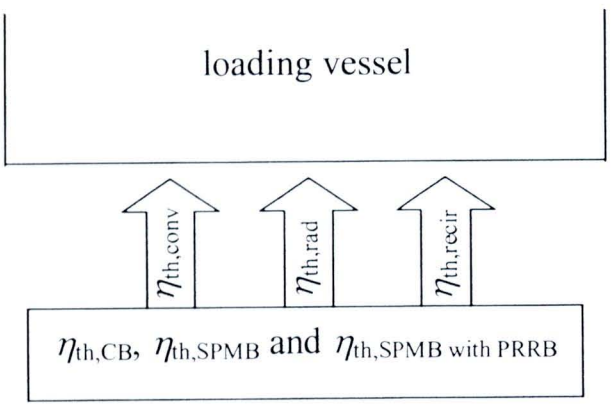


Figure D.1 Simplified model for contribution of thermal efficiency.

$$\eta_{\text{th,rad}} = \frac{\left|q^{n}(\tau_{\text{E}})\right| F_{\text{i}\to\text{j}} A}{CL} \times 100\% \tag{D.2}$$

$$F_{\text{i}\to\text{j}} = \frac{1}{2}\left\{S - \left[S^{2} - 4\left(\frac{r_{\text{j}}}{r_{\text{i}}}\right)^{2}\right]^{1/2}\right\} \tag{D.3}$$

$$S = 1 + \frac{1 + R_{\text{j}}^{2}}{R_{\text{i}}^{2}} \tag{D.4}$$

$$R_{\text{i}} = \frac{r_{\text{i}}}{H} \tag{D.5}$$

$$R_{\text{j}} = \frac{r_{\text{j}}}{H} \tag{D.6}$$

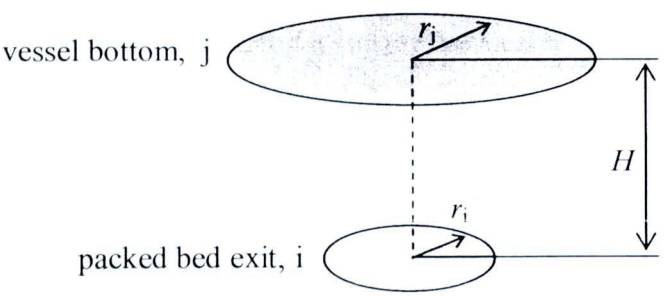


Figure D.2 View factor model for coaxial parallel disks [63].

where $F_{\text{i}\to\text{j}}$ is view factor from packed bed exit to vessel bottom, r_{i} is radius of packed bed exit in m, r_{j} is radius of vessel bottom in m, and H is distance between packed bed exit and vessel bottom in m.

The $\eta_{\text{th,SPMB}}$ and $\eta_{\text{th,SPMB with PRRB}}$ can be described in Eqs. (D.7) and (D.8), respectively. For the left hand side of those equations, that are got by experimental results in chapters 4 and 5. The $\eta_{\text{th,rad}}$ in Eq. (D.7) is estimated by Eq. (D.2) then the $\eta_{\text{th,conv}}$ can be solved. The $\eta_{\text{th,recir}}$ is calculated from Eq. (D.8) when using the $\eta_{\text{th,SPMB}}$ and $\eta_{\text{th,SPMB with PRRB}}$ from experimental data at same condition (the measured $\eta_{\text{th,SPMB}}$ is lower than one).

$$\eta_{\text{th,SPMB}} = \eta_{\text{th,conv}} + \eta_{\text{th,rad}} \tag{D.7}$$

$$\eta_{\text{th,SPMB with PRRB}} = \eta_{\text{th,SPMB}} + \eta_{\text{th,recir}} \tag{D.8}$$

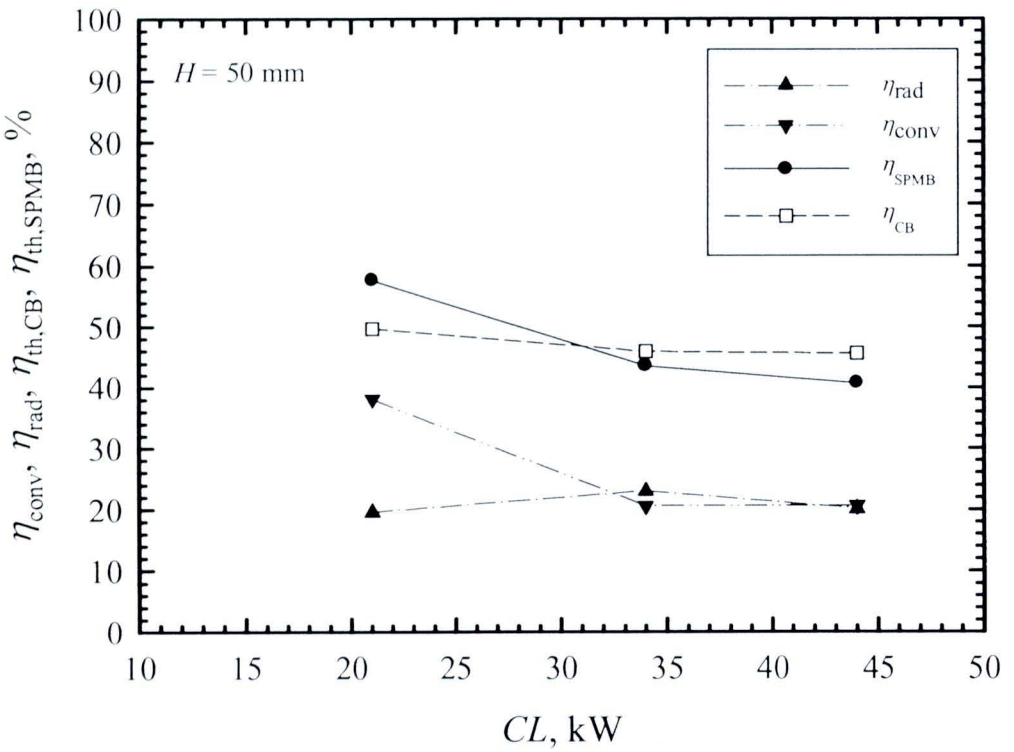


Figure D.3 Contribution of thermal efficiency of the SPMB at $H = 50$ mm.

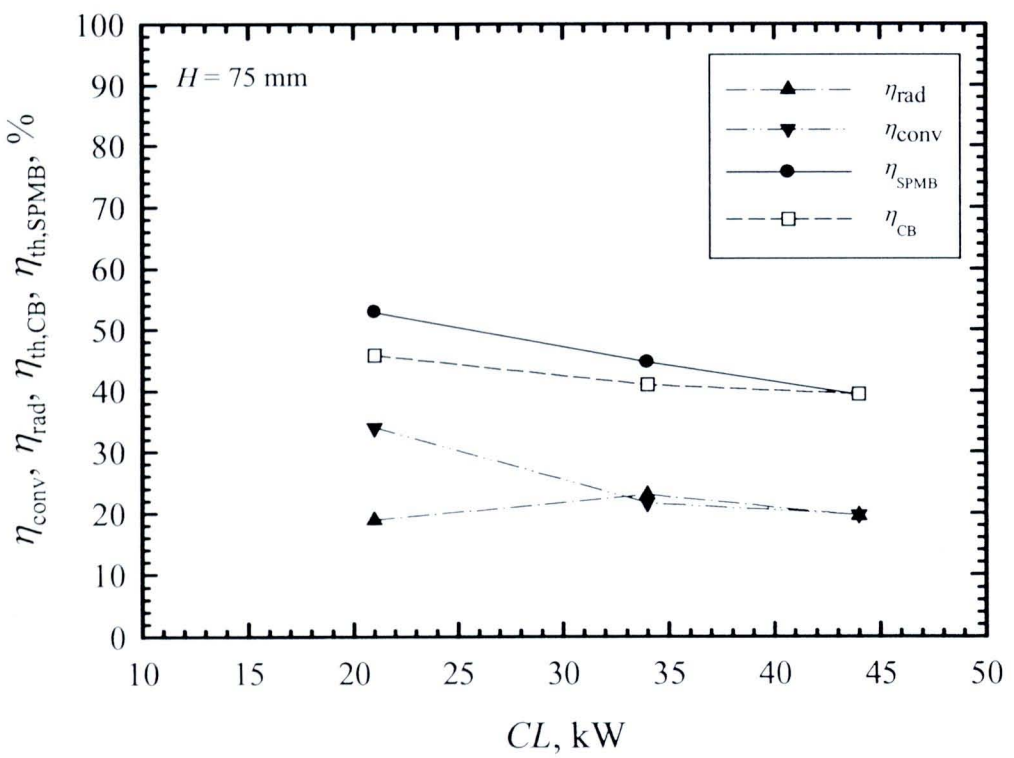


Figure D.4 Contribution of thermal efficiency of the SPMB at $H = 75$ mm.

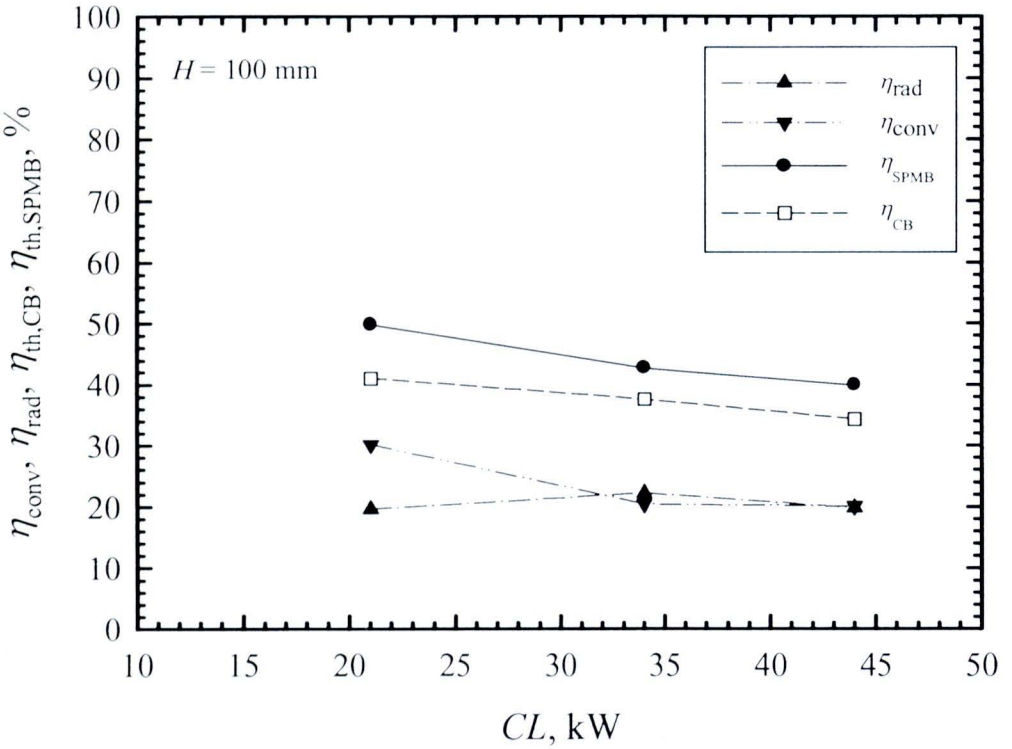


Figure D.5 Contribution of thermal efficiency of the SPMB at $H = 100$ mm.

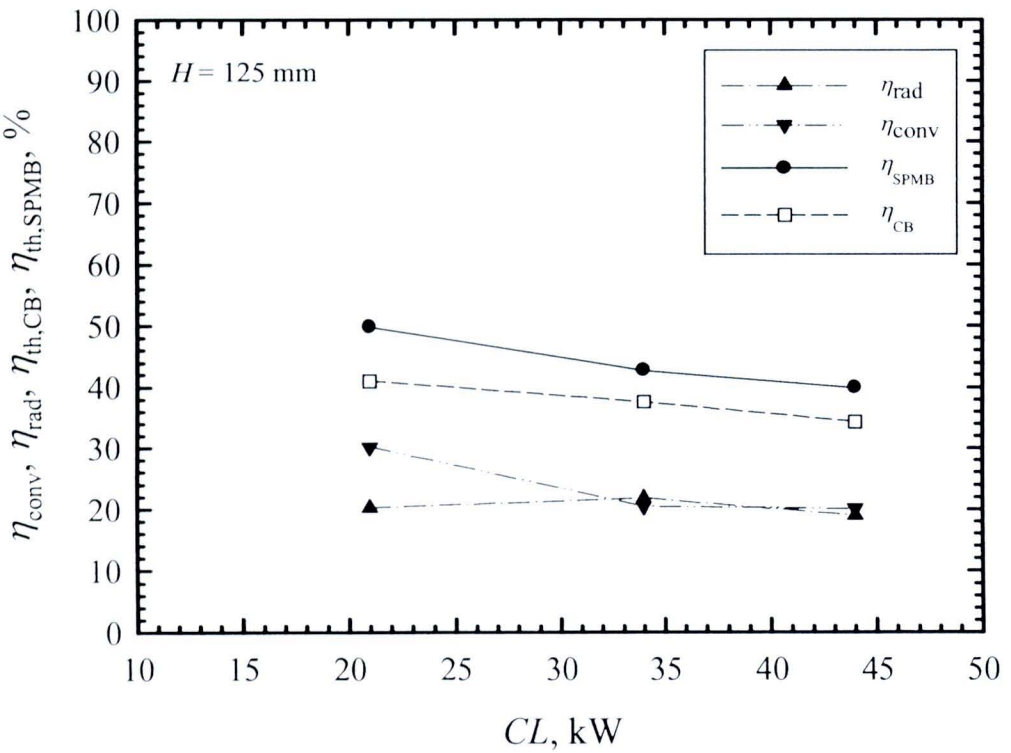


Figure D.6 Contribution of thermal efficiency of the SPMB at $H = 125$ mm.

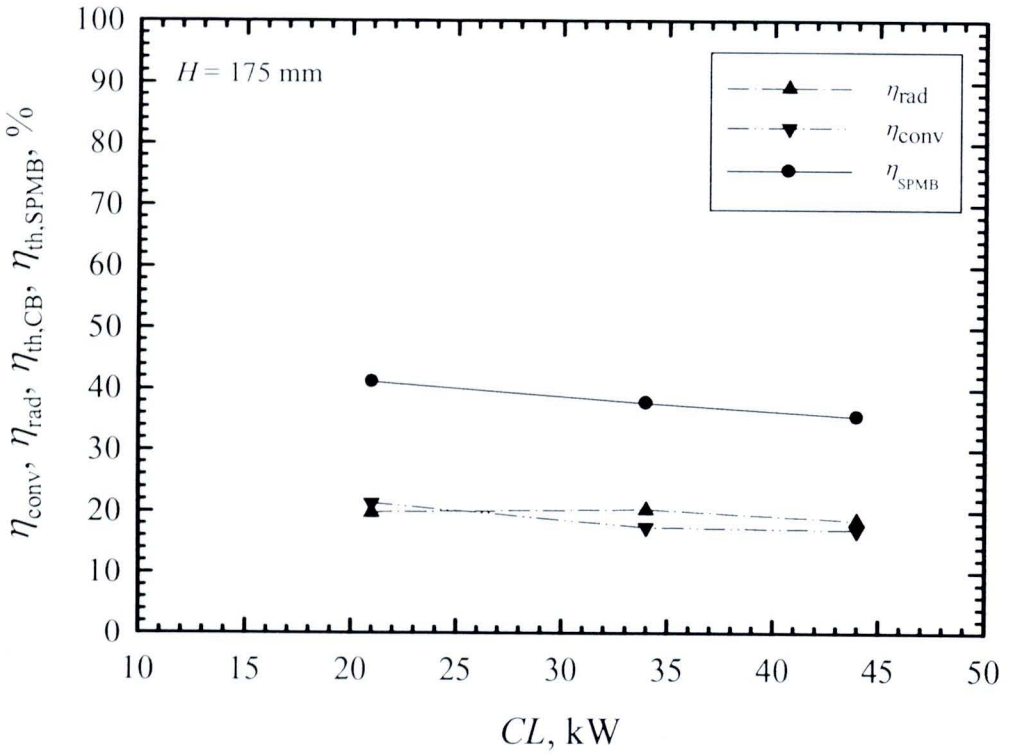


Figure D.7 Contribution of thermal efficiency of the SPMB at $H = 175$ mm.

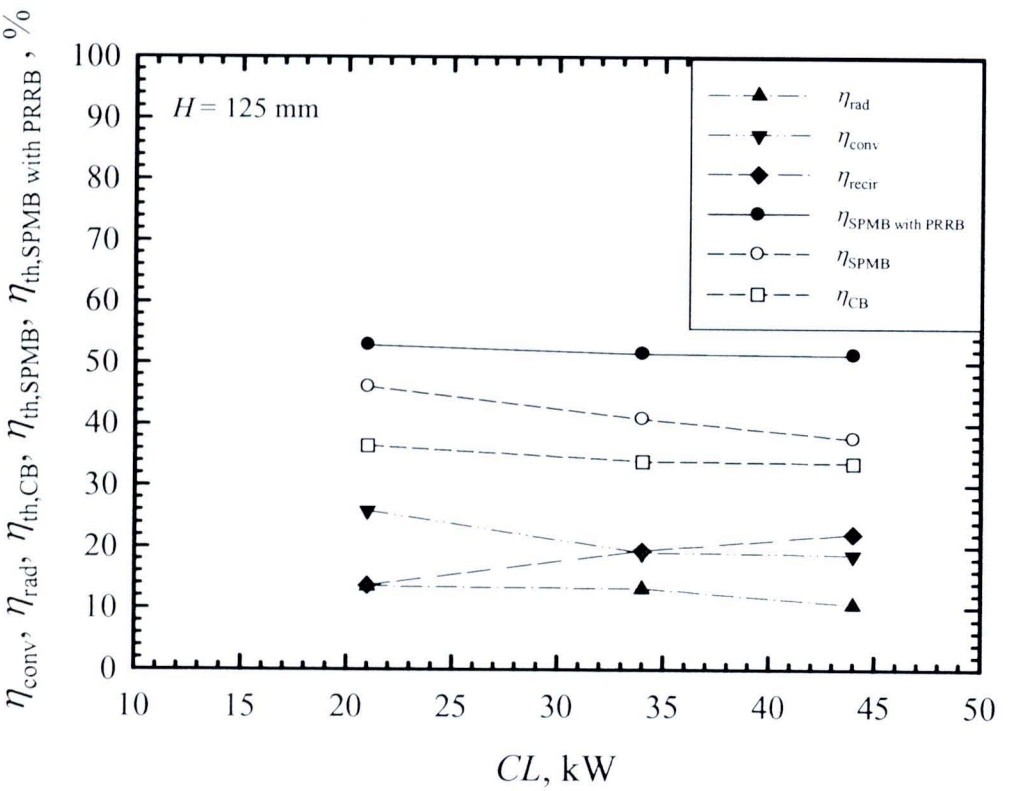


Figure D.8 Thermal efficiency contribution of the SPMB with PRRB at $H = 125$ mm.

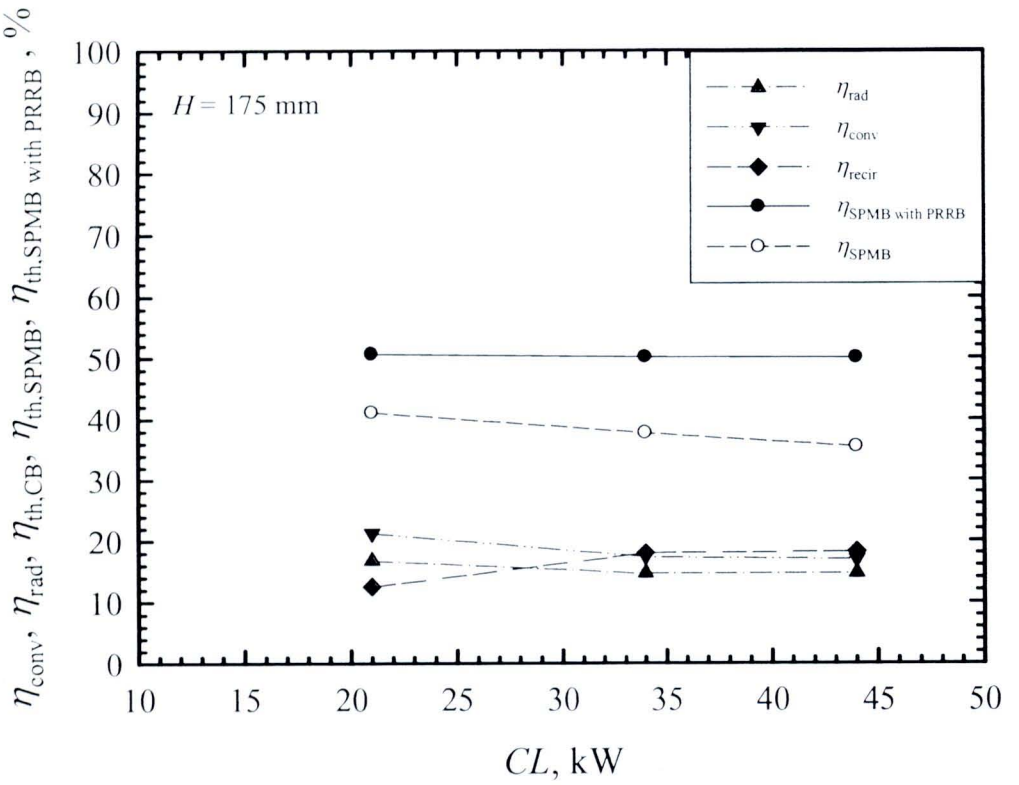


Figure D.9 Thermal efficiency contribution of the SPMB with PRRB at H = 175 mm.

APPENDIX E

Drawing of the SPMB and PRRB

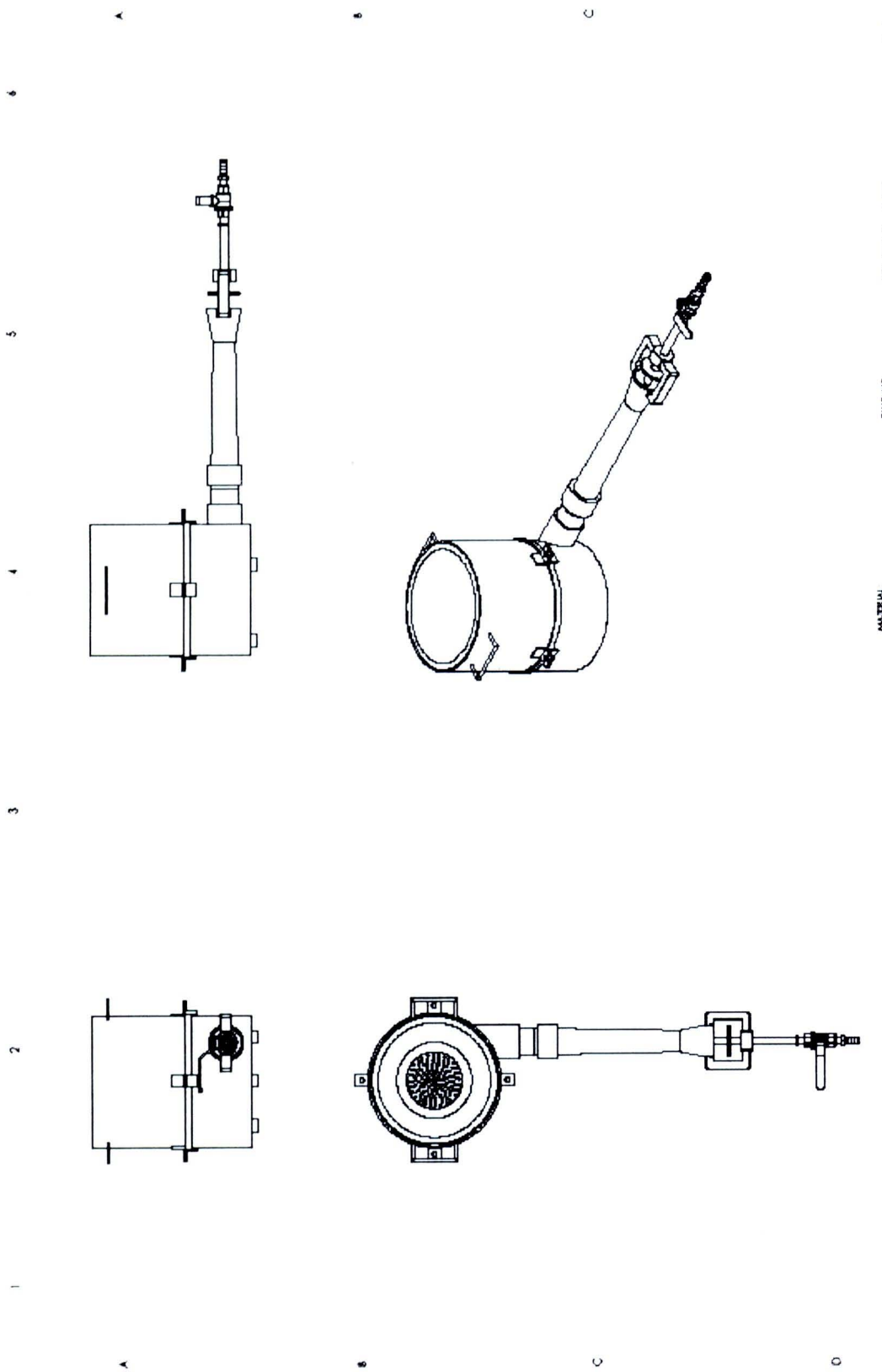


Figure E.1 Drawing of self-aspirating porous medium burner (SPMB).

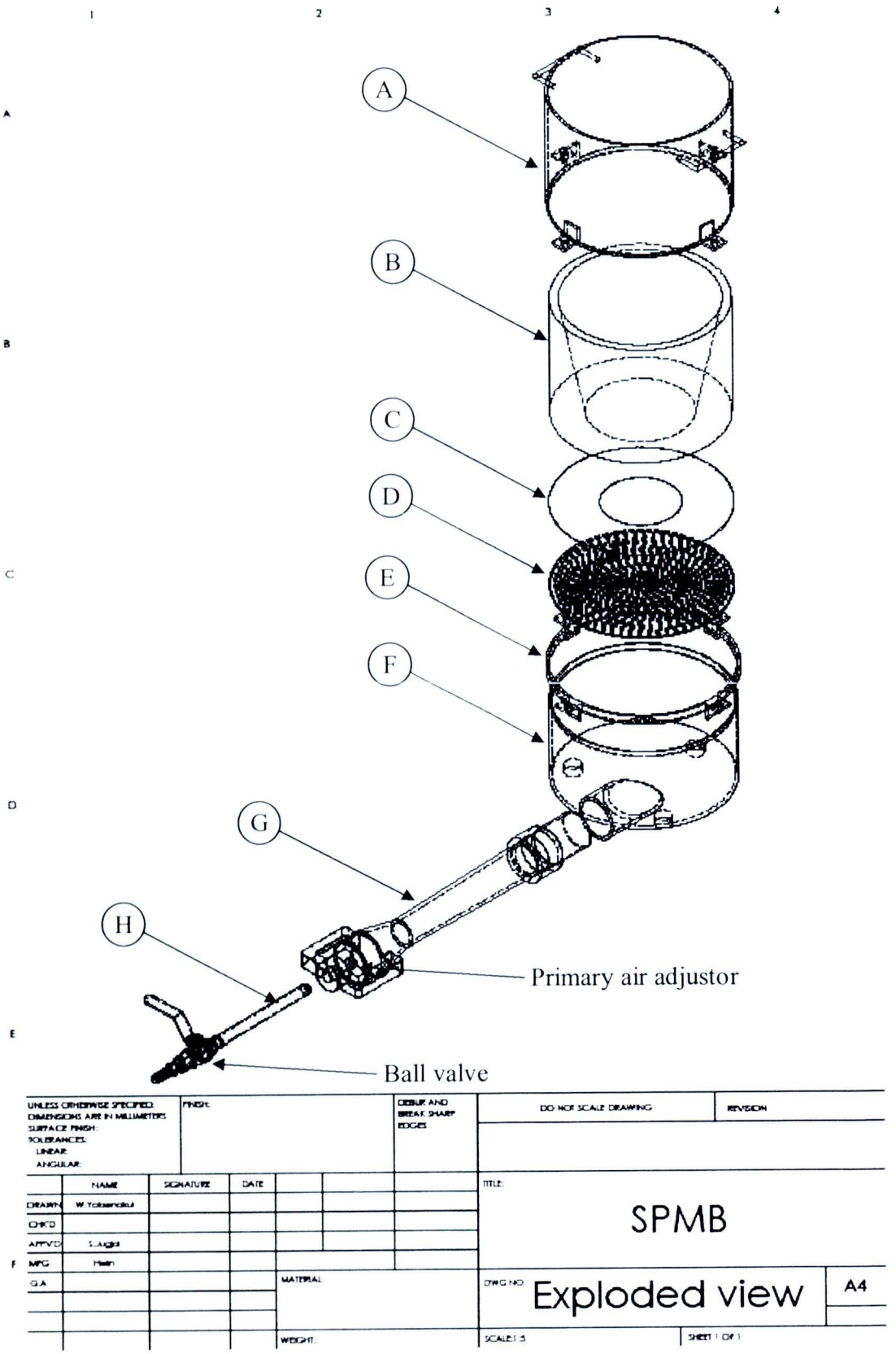


Figure E.2 Assembly of self-aspirating porous medium burner (SPMB).

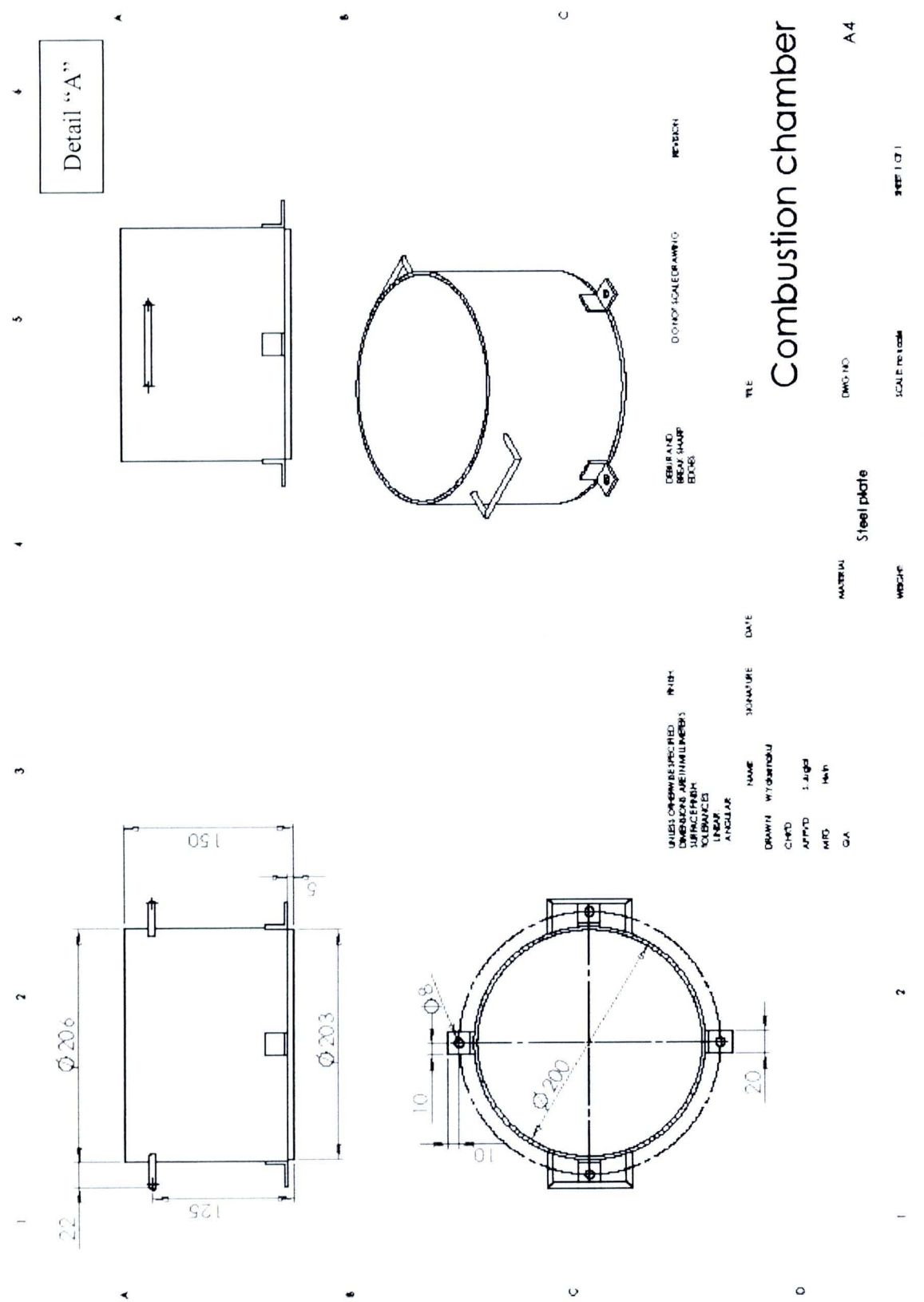


Figure E.3 Drawing of combustion chamber (SPMB).

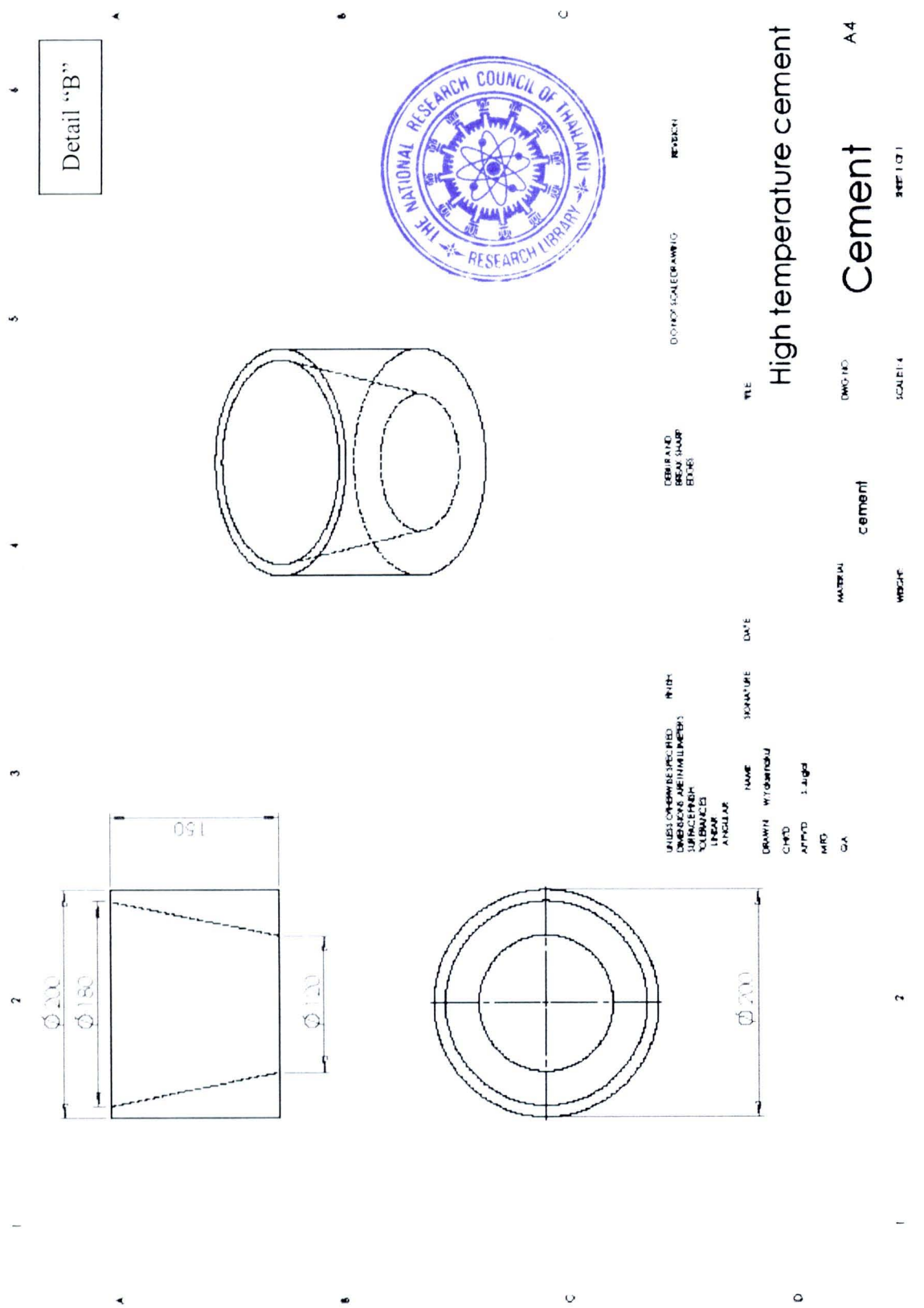


Figure E.4 Drawing of high temperature cement (SPMB).

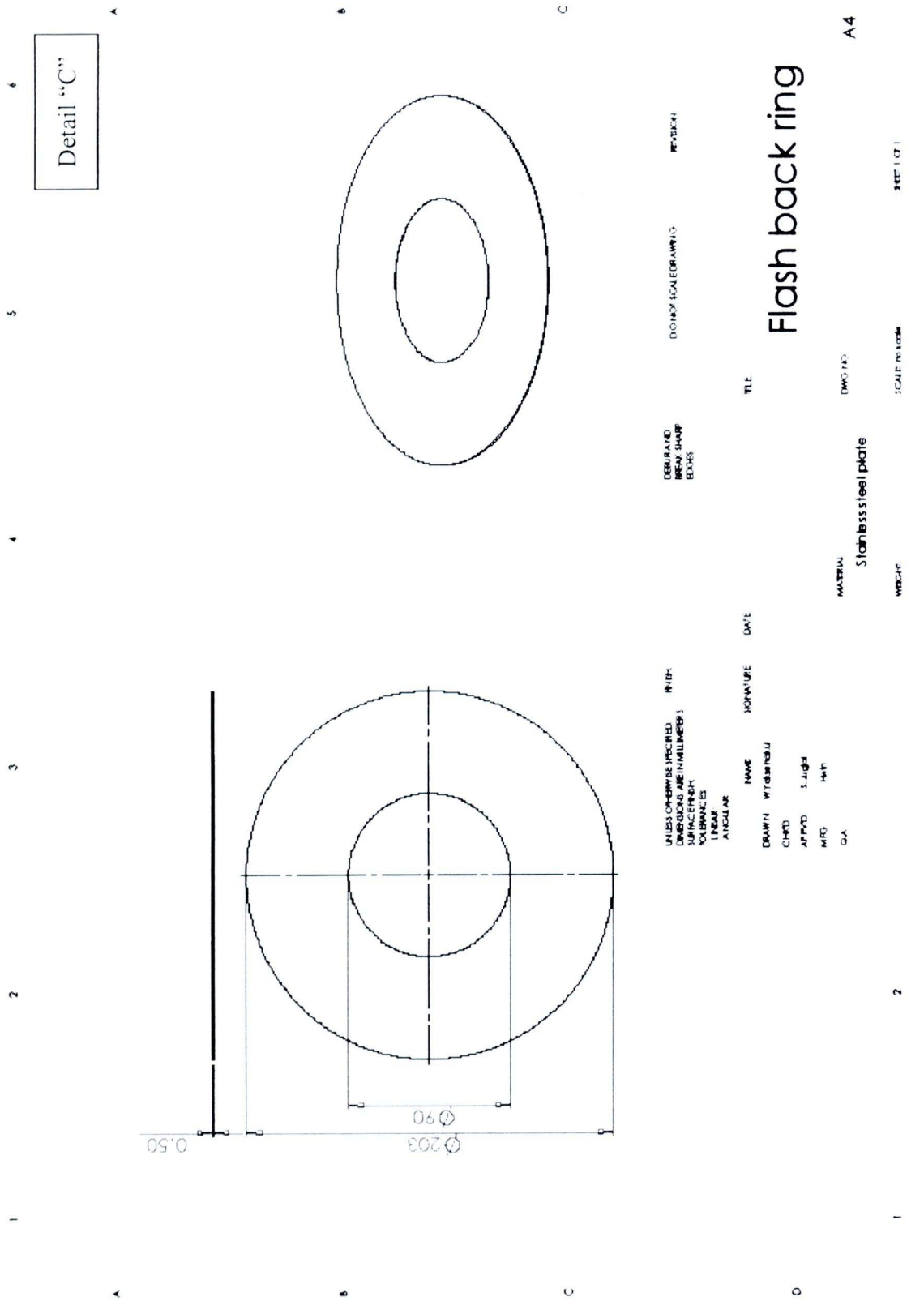


Figure E.5 Drawing of flash back ring (SPMB).

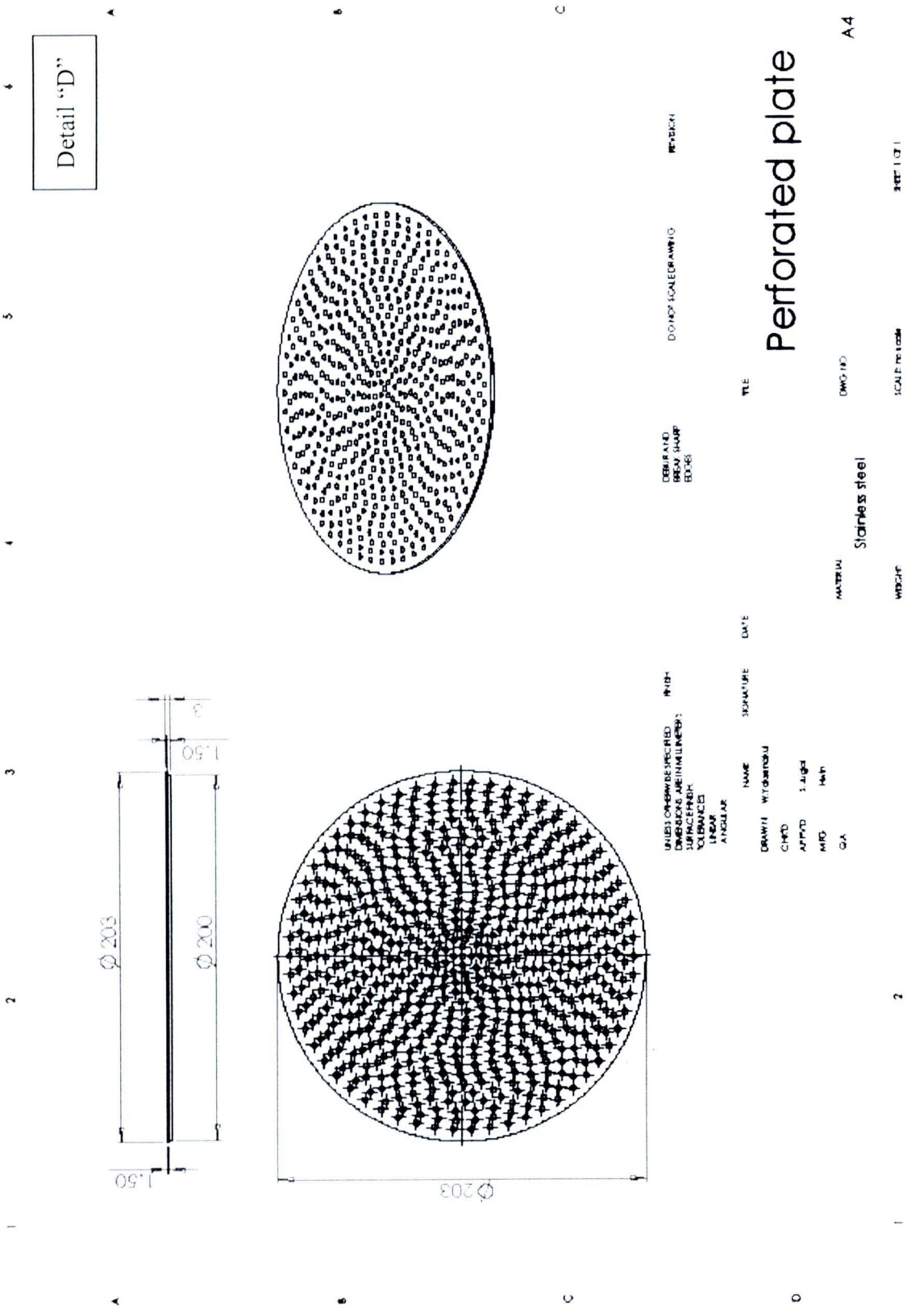


Figure E.6 Drawing of perforated stainless steel plate (SPMB).

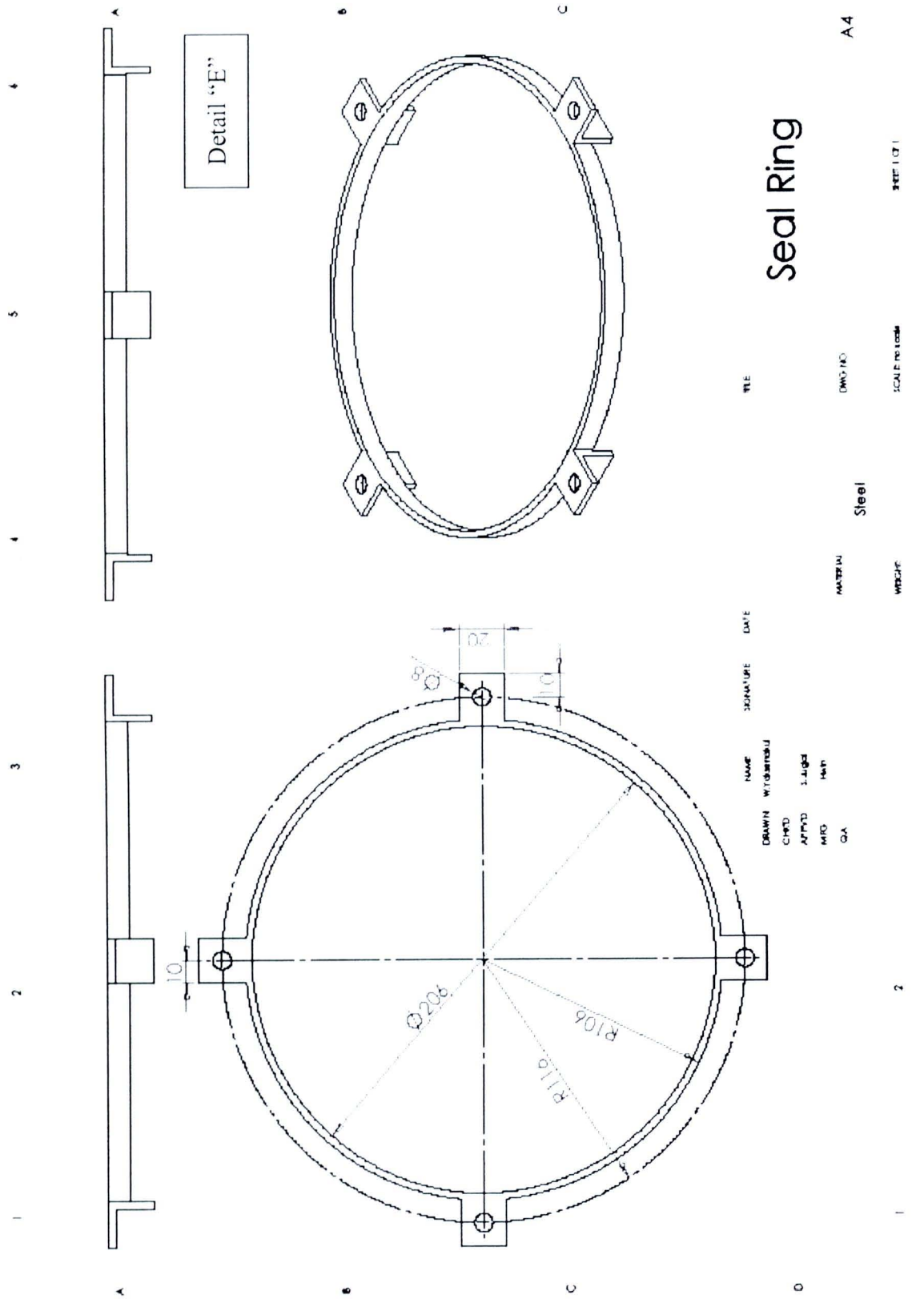


Figure E.7 Drawing of seal ring (SPMB).

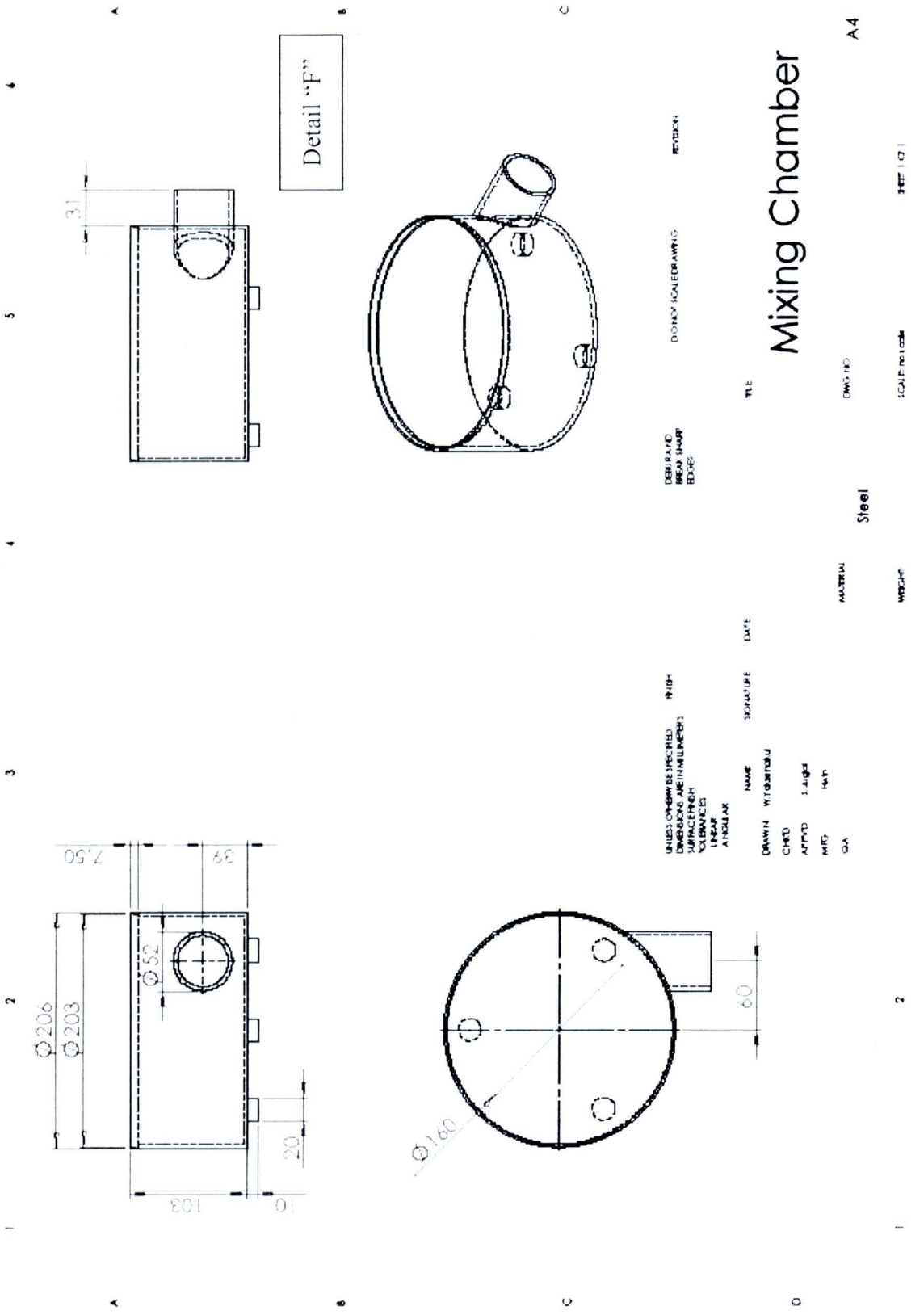


Figure E.8 Drawing of mixing chamber (SPMB).

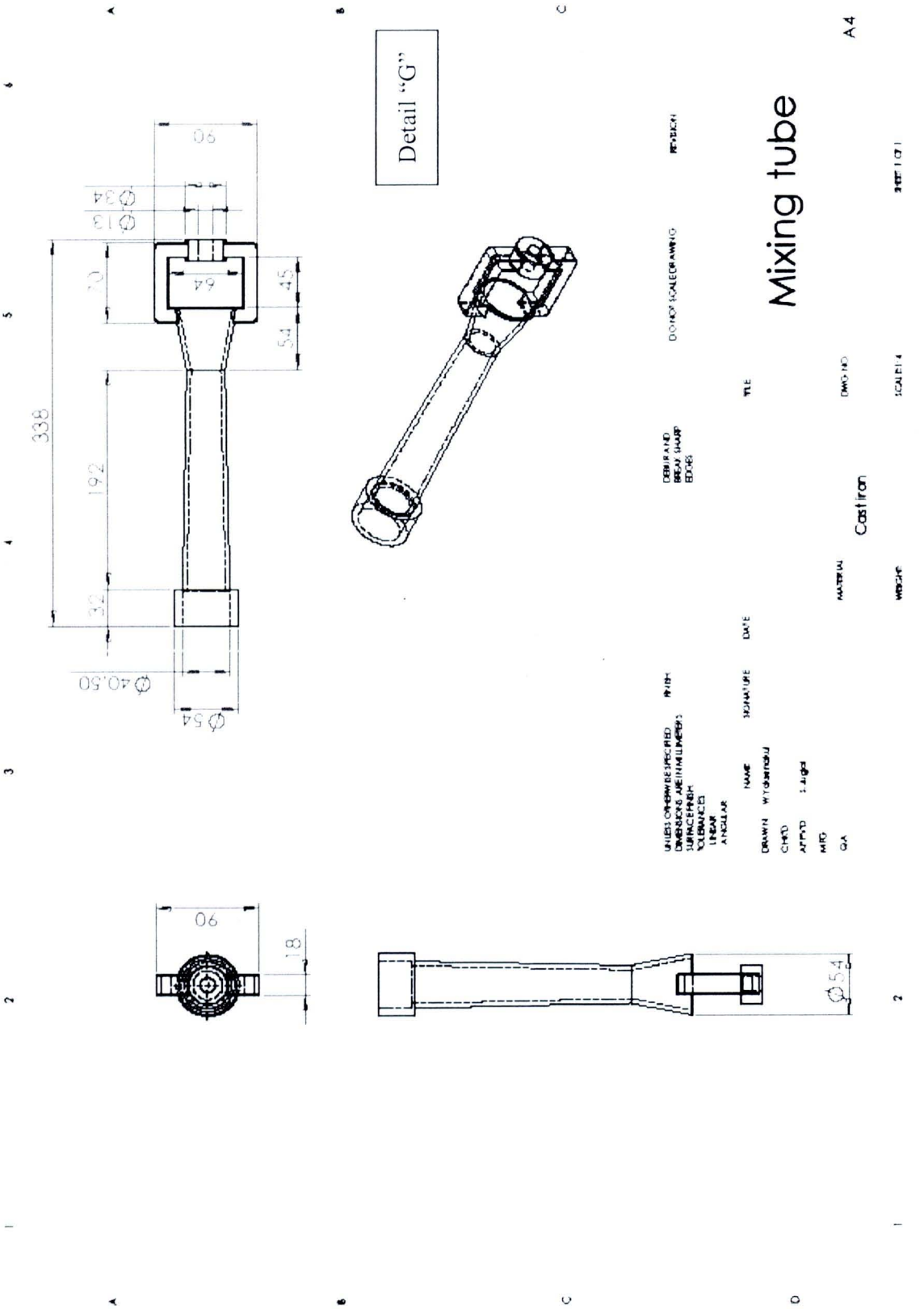


Figure E.9 Drawing of mixing tube (SPMB).

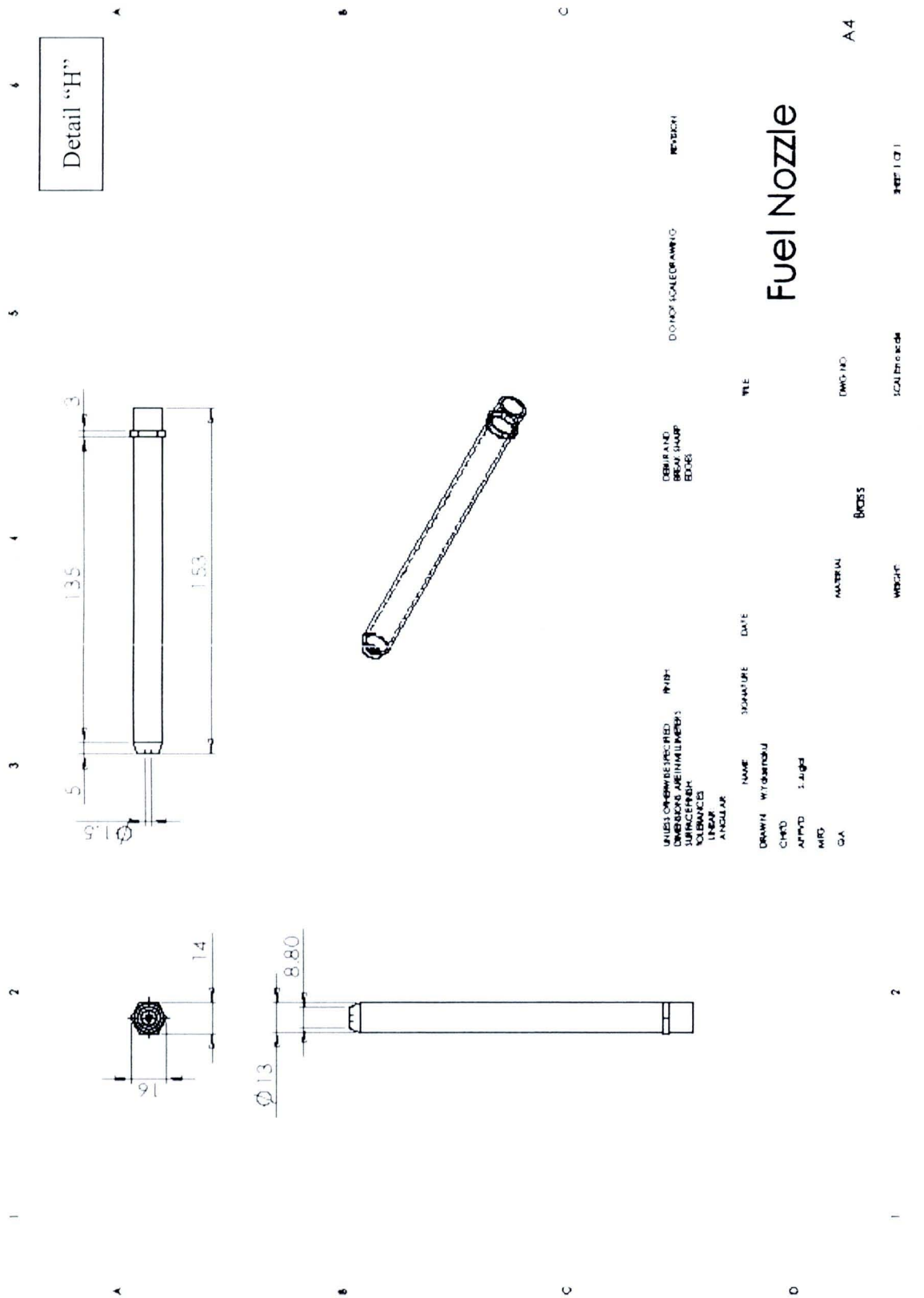


Figure E.10 Drawing of gas fuel nozzle (SPMB).

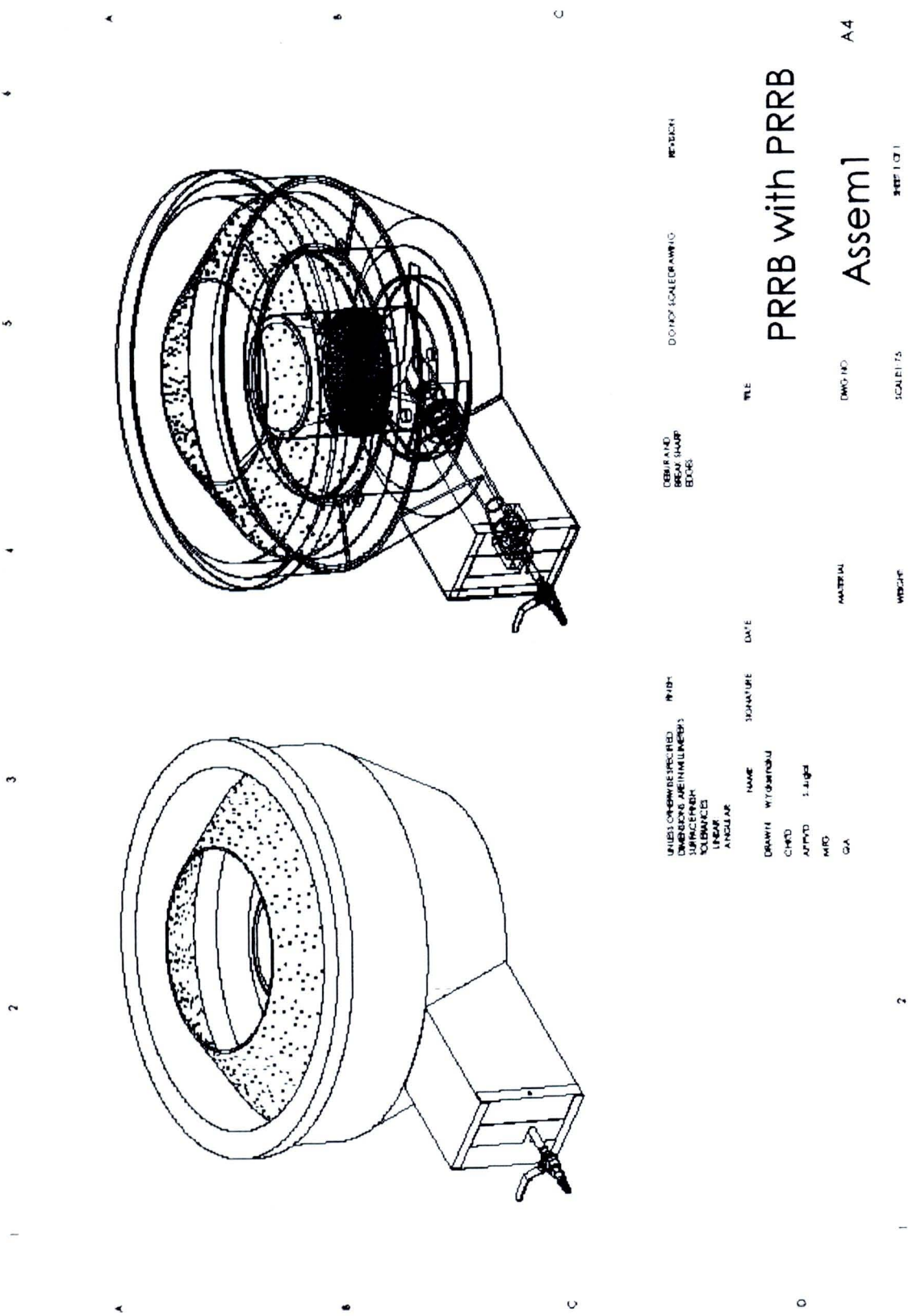
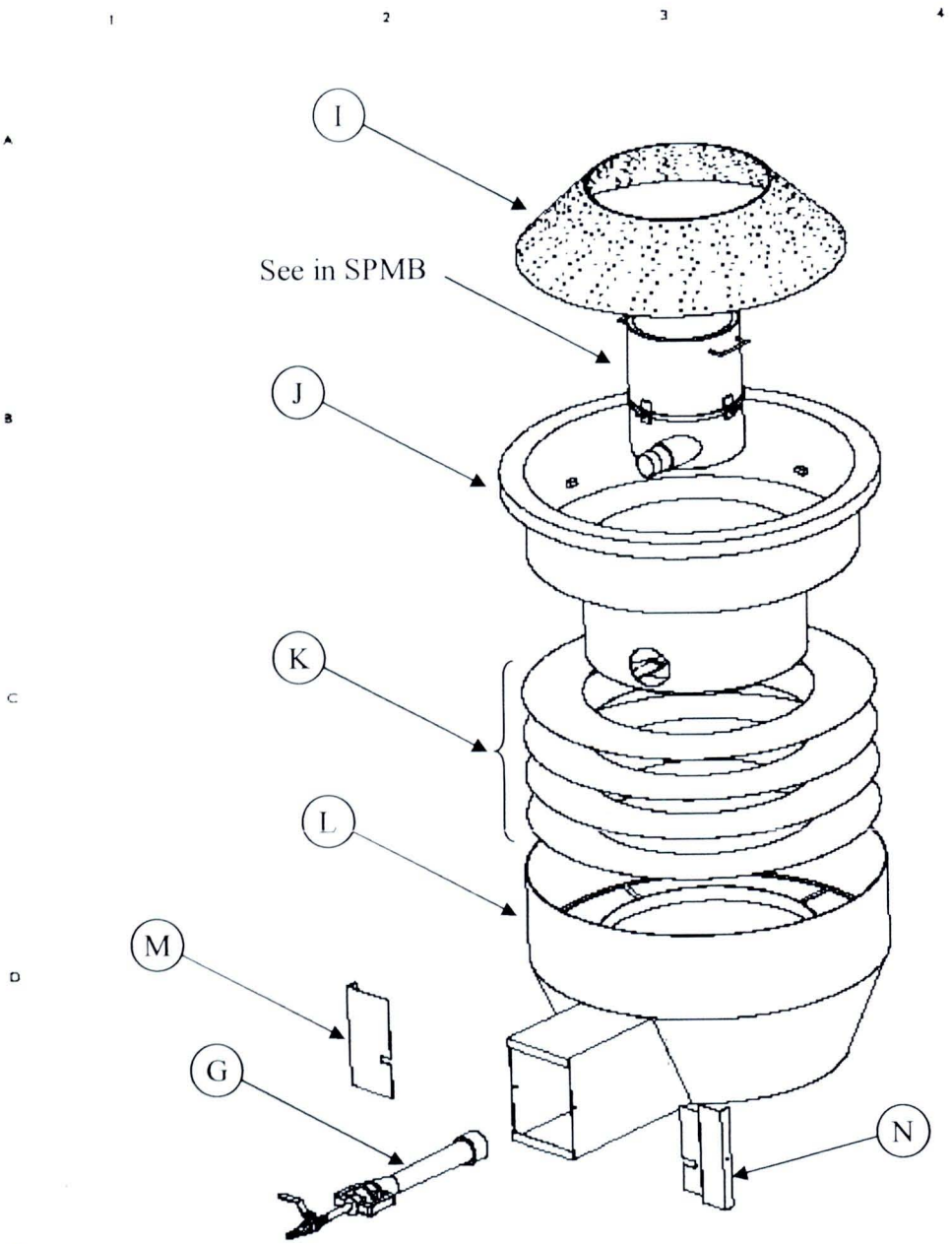


Figure E.11 Drawing of porous radiant recirculated burner (PRRB).



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:				DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE				TITLE: SPMB with PRRB	
DRAWN	W. Yolasandoul							
CHKD								
APPVD	S. Jugjai							
MFG	Hsin							
Q.A				MATERIAL:			DWG NO: Explode view	A4
				WEIGHT:			SCALE: 1:10	SHEET 1 OF 1

Figure E.12 Assembly of porous radiant recirculated burner (PRRB).

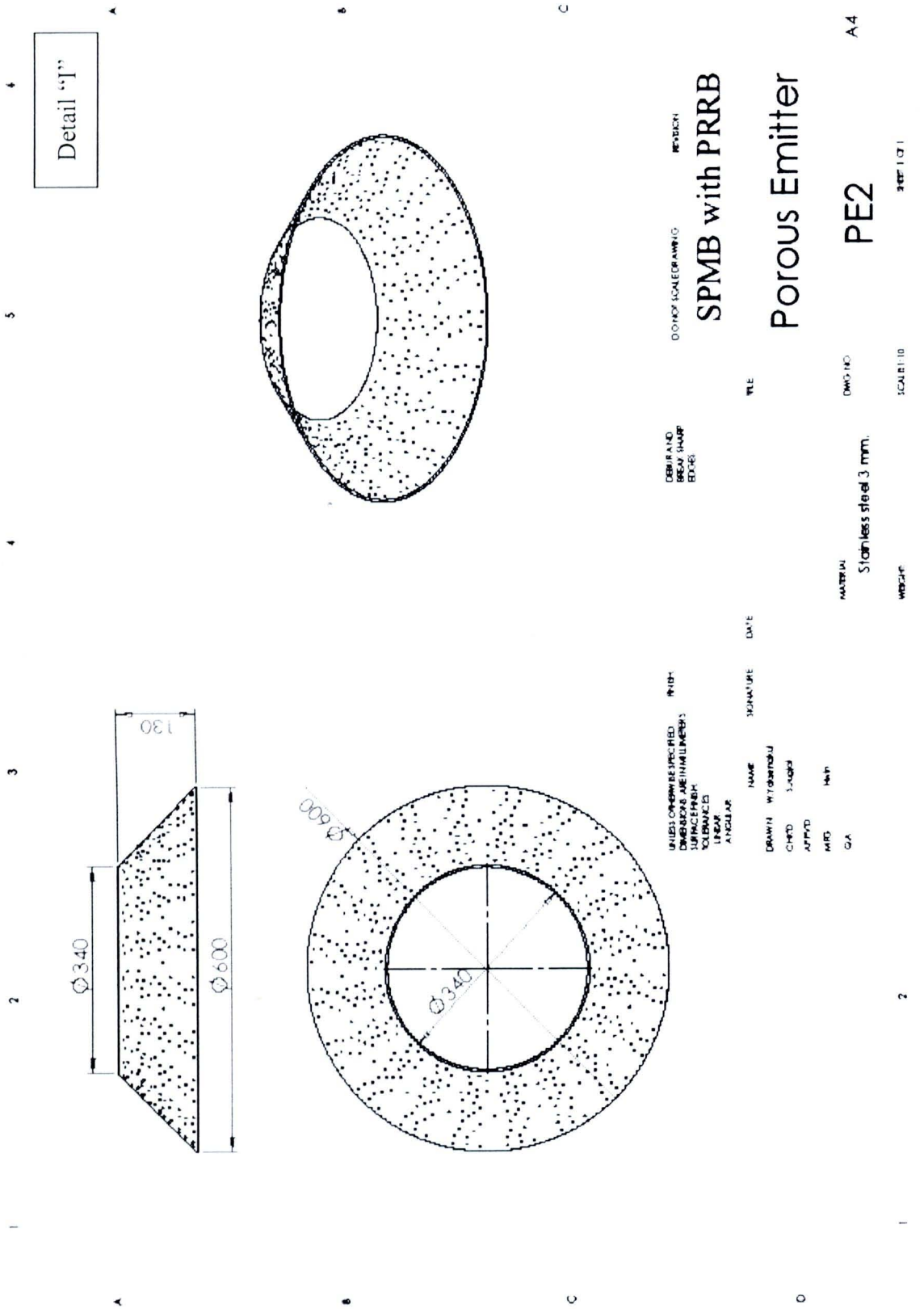


Figure E.13 Drawing of emitting porous medium (PRRB).

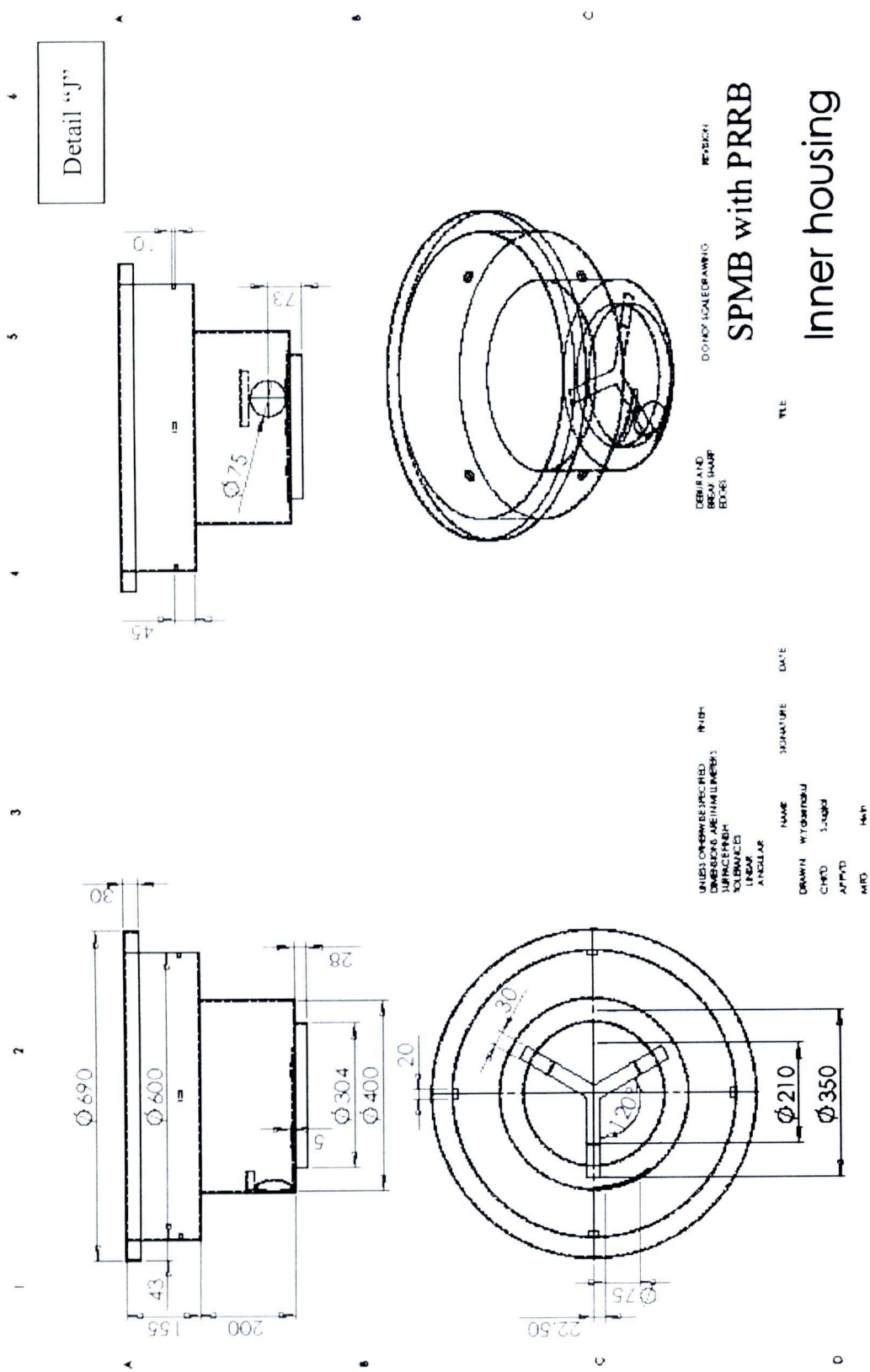


Figure E.14 Drawing of inner housing (PRRB).

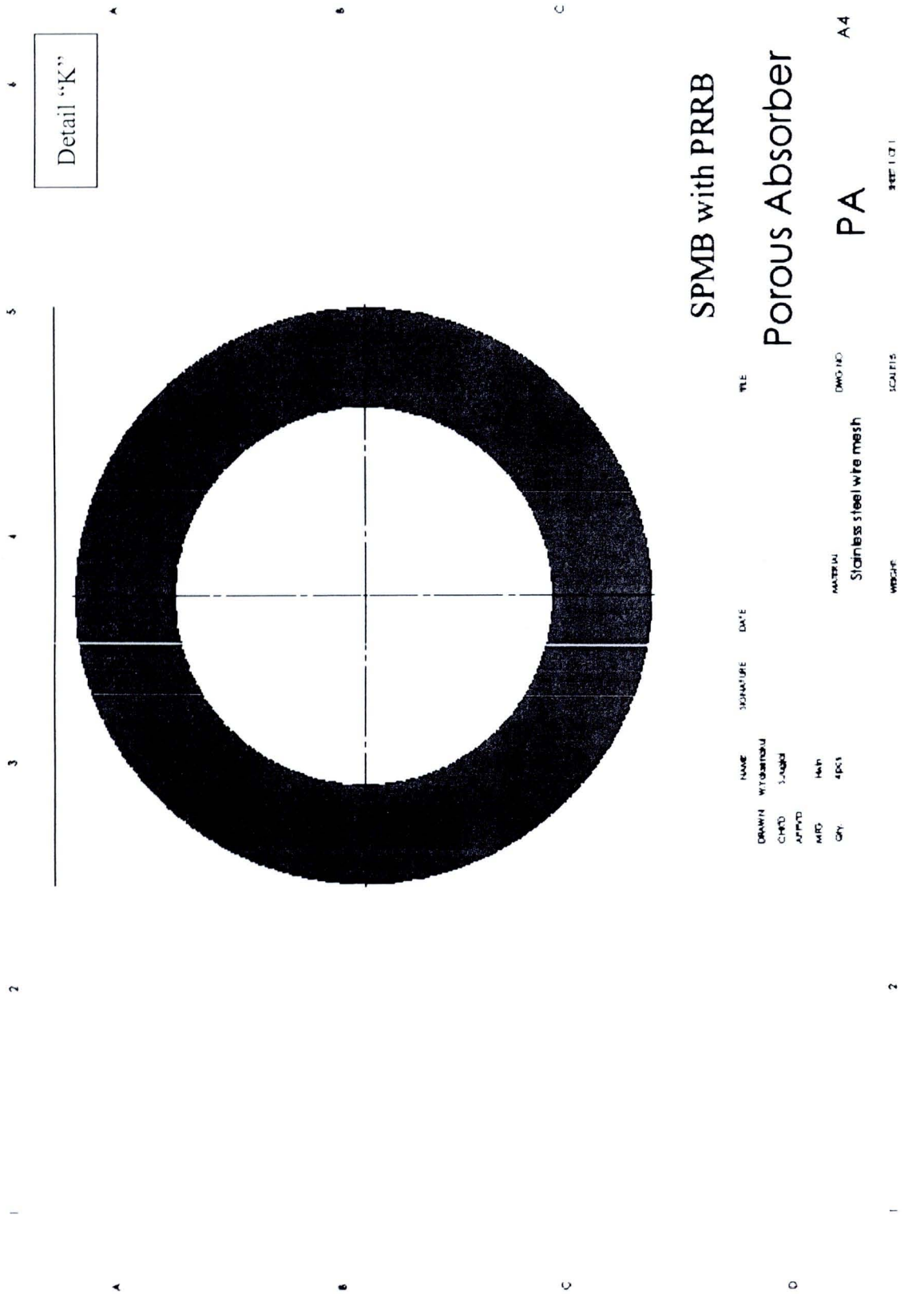


Figure E.15 Drawing of absorbing porous medium (PRRB).

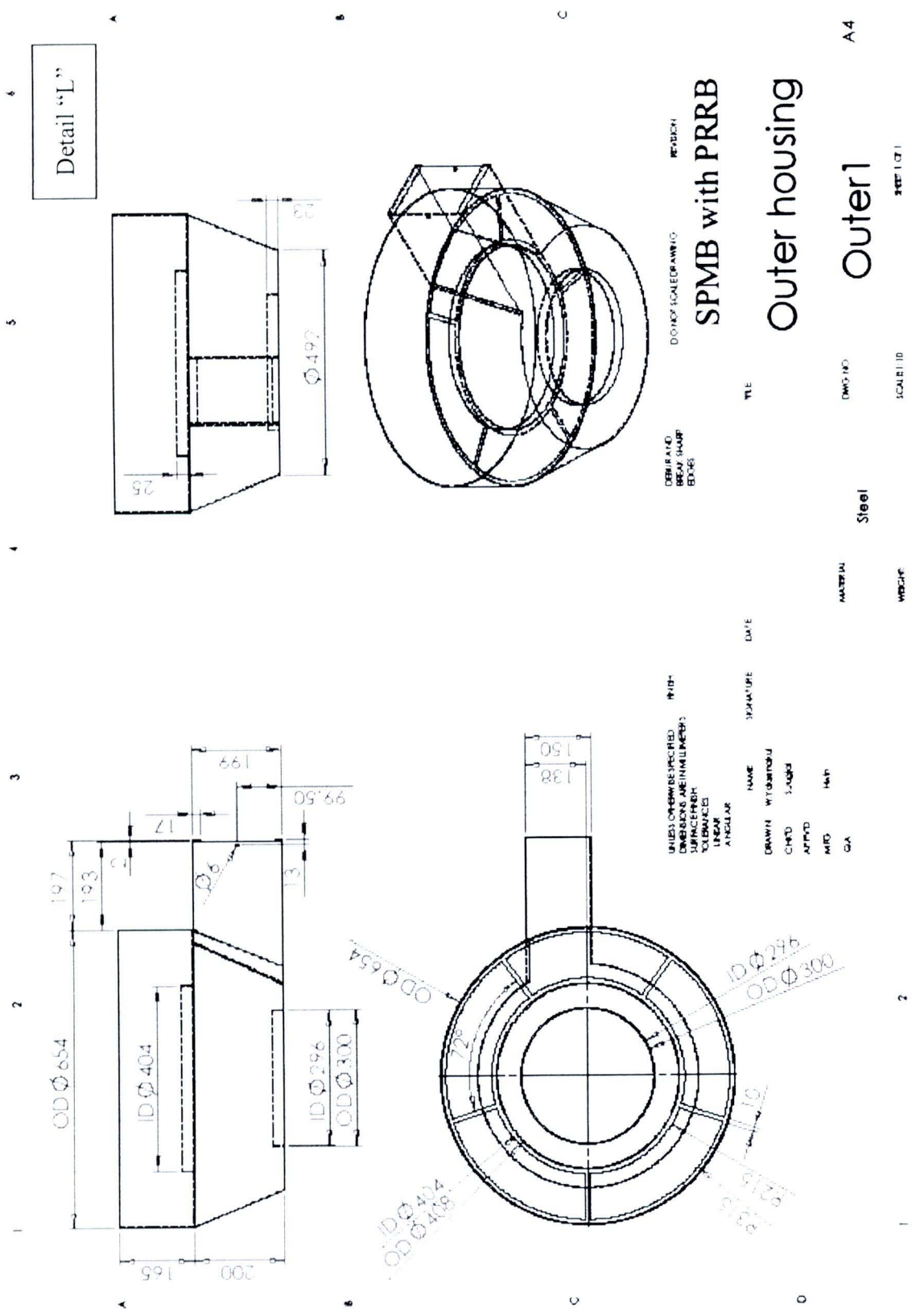


Figure E.16 Drawing of outer housing (PRRB).

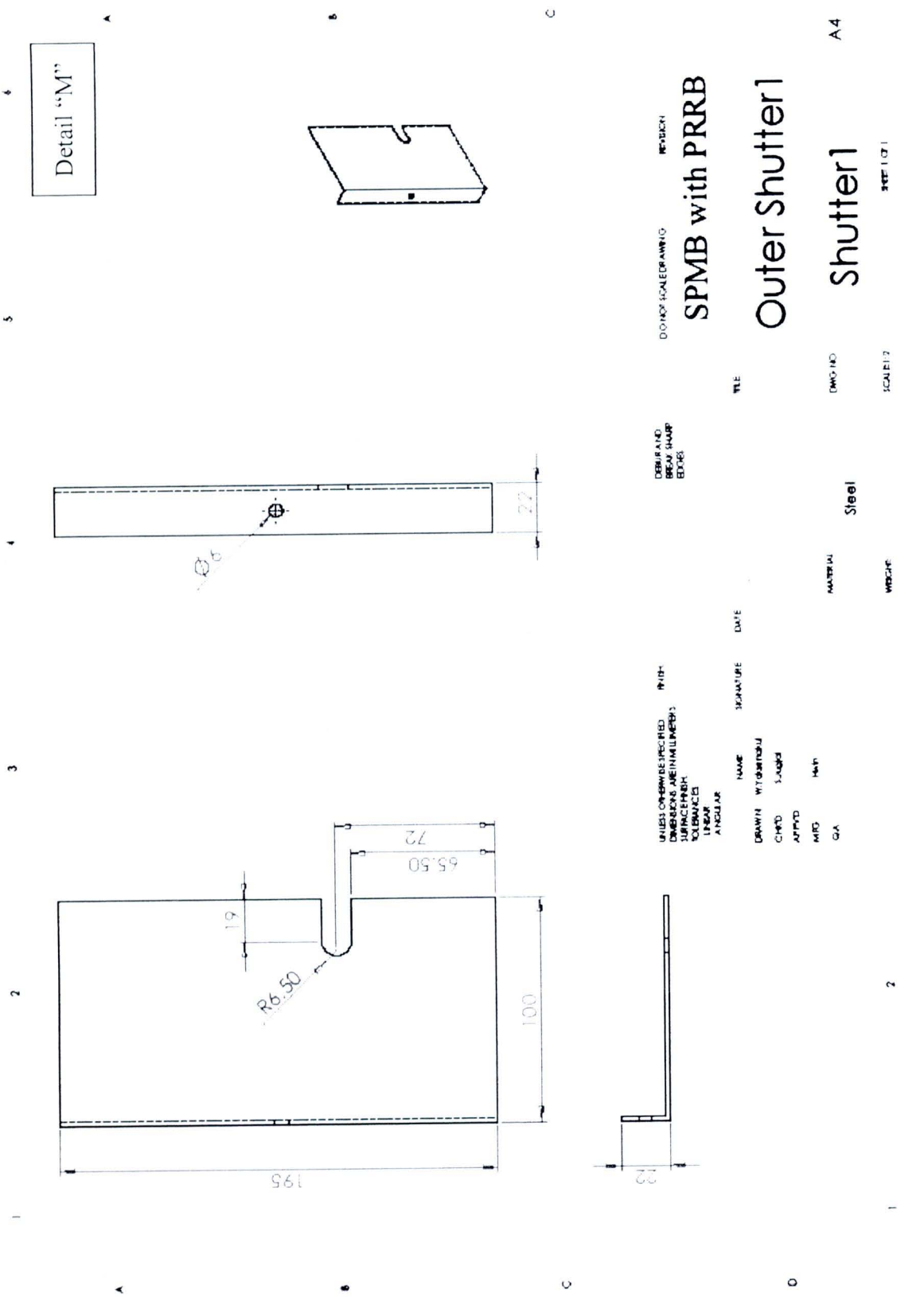


Figure E.17 Drawing of shutter 1 (PRRB).

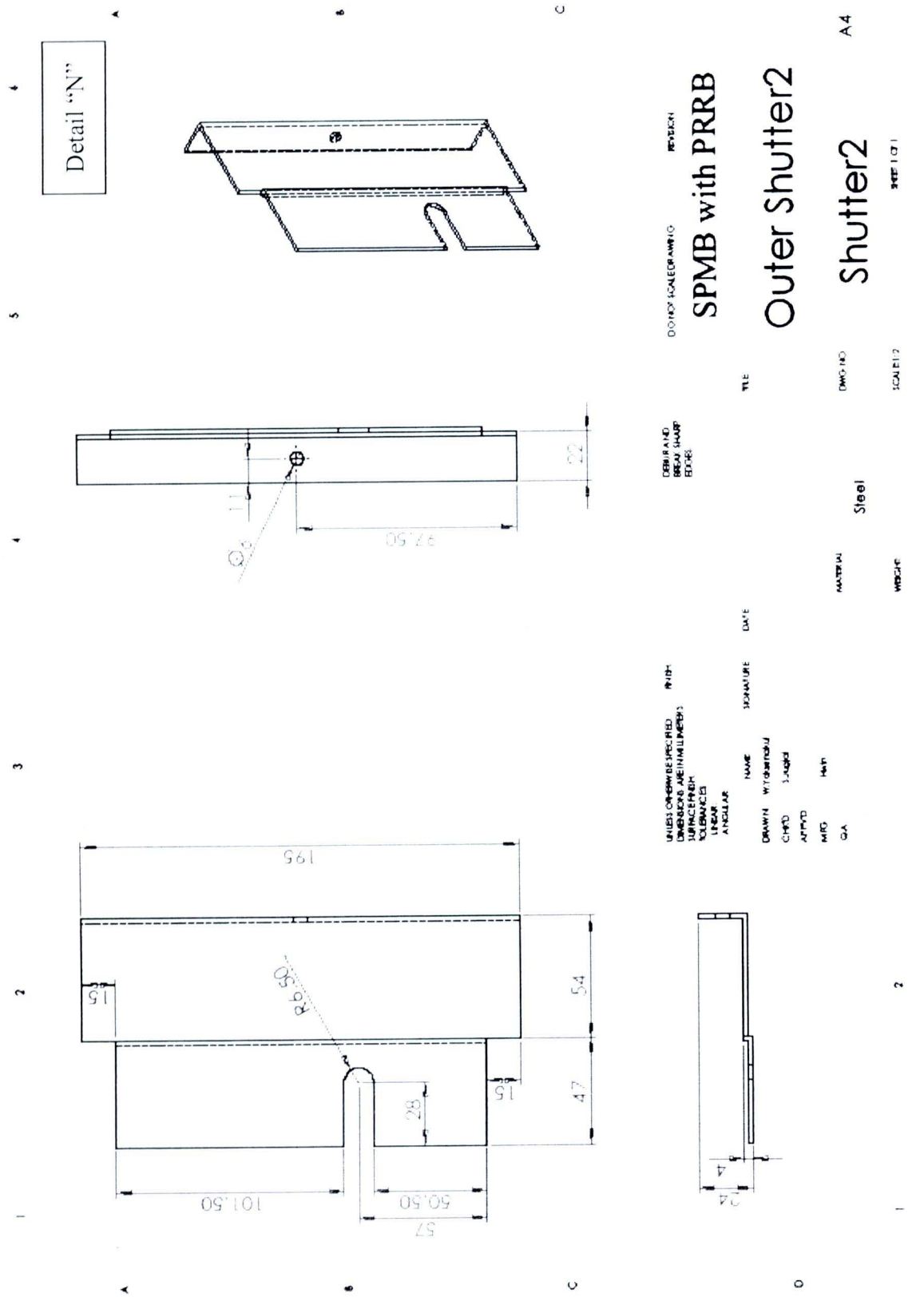


Figure E.18 Drawing of shutter 2 (PRRB).

CIRRICULUM VITAE

NAME Mr. Wasan Yoksenakul

DATE OF BIRTH 8 December 1979

EDUCATIONAL RECORD

HIGH SCHOOL	High School Graduation Rajsima Wittayalai School, 1997
BACHELOR'S DEGREE	Bachelor of Engineering (Mechanical Engineering) Siam University, 2002
MASTER'S DEGREE	Master of Engineering (Mechanical Engineering) King Mongkut's University of Technology Thonburi 2005
DOCTORAL DEGREE	Doctor of Engineering (Mechanical Engineering) King Mongkut's University of Technology Thonburi 2011

PUBLICATIONS

Yoksenakul, W. and Jugjai, S., 2009, "Self-aspirating porous burner (SPB) for small and medium scale enterprises (SMEs): A burner design", **Sustainable Development to Save the Earth: Technologies and Strategies Vision 2050 (SDSE 2008)**, 7-9 April, Bangkok, Thailand.

Yoksenakul, W. and Jugjai, S., 2010, "Self-aspirating porous burner (SPB) with matrix-stabilized flame for small and medium scale enterprises (SMEs)", **The 1st TSME International Conference on Mechanical Engineering**, 20-22 October, Ubon Ratchathani, Thailand.

Yoksenakul, W. and Jugjai, S., 2011, "Thermal efficiency of self-aspirating porous burner for small and medium scale enterprises (SMEs)", **The 2nd TSME International Conference on Mechanical Engineering**, 19-21 October, Krabi, Thailand.

Yoksenakul, W. and Jugjai, S., 2011, "Design and development of a SPMB (self-aspirating, porous medium burner) with a submerged flame", **Energy**, Vol. 36, pp. 3092-3100.

King Mongkut's University of Technology Thonburi

Agreement on Intellectual Property Rights Transfer for Postgraduate Students

Date **7 September 2011**

Name **Mr.Wasan** Surname **Yoksenakul** Student Number **48500205**

who is a student of King's Mongkut's University of Technology Thonburi (KMUTT) in

☐ Graduate Diploma ☐ Master Degree ☑ Doctoral Degree

Program **Doctor of Engineering** Field of Study **Mechanical Engineering** Faculty **Engineering**

Home Address **42/122 Soi 3 Rama 2** Road, **Bangmod, Jomthong, Bangkok**

Postal Code **10150** Country **Thailand**

I, as 'Transferer', hereby transfer the ownership of my thesis copyright to King's Mongkut's University of Technology Thonburi who has appointed (Dean's name) **Assoc.Prof.Dr.Booncharoen Sirinaovakul** Dean of Faculty of **Engineering** to be 'Transferee' of copyright ownership under the 'Agreement' as follows.

1. I am the author of the thesis entitled **Improvement of Thermal Efficiency of Heat-Recirculating Gas Burner** under the supervision **of Assoc.Prof.Dr.Somchai Chanchaona** who is my supervisor, and/or **Prof. Dr. Sumrerng Jugjai** who is/are my co-supervisor(s), in accordance with the Thai Copyright Act B.E. 2537. The thesis is a part of the curriculum of KMUTT.

2. I hereby transfer the copyright ownership of all my works in the thesis to KMUTT throughout the copyright protection period in accordance with the Thai Copyright Act B.E. 2537, effective on the approval date of thesis proposal consented by KMUTT.

3. To have the thesis distributed in any form of media, I shall in each and every case stipulate the thesis as the work of KMUTT.

4. For my own distribution of thesis or the reproduction, adjustment, or distribution of thesis by the third party in accordance with the Thai Copyright Act B.E. 2537 with remuneration in return, I am subject to obtain a prior written permission from KMUTT.

5. To use any information from my thesis to make an invention or create any intellectual property works within ten (10) years from the date of signing this Agreement, I am subject to obtain prior written permission from KMUTT, and KMUTT is entitled to have intellectual property rights on such inventions or intellectual property works, including entitling to take royalty from licensing together with the distribution of any benefit deriving partly or wholly from the works in the future.

conforming with the Regulation of King Mongkut's Institute of Technology Thonburi *Re* the Administration of Benefits deriving from Intellectual Property B.E. 2538.

6. If the benefits arise from my thesis or my intellectual property works owned by KMUTT, I shall be entitled to gain the benefits according to the allocation rate stated in the Regulation of King Mongkut's Institute of Technology Thonburi *Re* the Administration of Benefits deriving from Intellectual Property B.E. 2538.

Signature.....Transferor

(**Mr. Wasan Yoksenakul**)

Student

Signature.....Transferee

(**Assoc. Prof. Dr. Piyabutr Wanichpongpan**)

Associate Dean for Academic Affairs (Acting for Dean)

Signature.....Witness

(**Asst. Prof. Dr. Pongpan Kaewtatip**)

Signature.....Witness

(**Prof. Dr. Sumrerng Jugjai**)