Modeling the IP - LP Turbines with PEPSE®

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ABSTRACT

The standard General Electric procedure for modeling the reheat turbine expansion line from the IP turbine inlet to the LP turbine exhaust compromises the accuracy of the IP turbine efficiency calculation to more closely match extraction temperatures. This paper develops a PEPSE® model which uses the G. E. procedures to find the correct efficiencies for the two turbines and a performance parameter which represents turbine spill strip leakage. Use of the model yields realistic comparisons of test data to design performance and indications of internal turbine condition.

INTRODUCTION

At many power plants, engineers have used manufacturer heat balances to calculate design turbine efficiencies. For a typical General Electric (G. E.) intermediate pressure (IP) turbine, acceptance test or routine performance test results show an efficiency as much as four percent above the design efficiency. Though this finding is encouraging to the engineers and owners of the turbine, it is not truly accurate. This is because the G. E. procedure for the reheat turbine expansion line was constructed to match, as closely as possible, both the power output of the turbine and the extraction temperatures. In doing so, the accuracy of knowing the IP turbine efficiency was compromised. Typically the efficiency from the manufacturer's heat balance is about four percent below the true IP efficiency.

This paper intends to describe a procedure to more accurately model the reheat turbine expansion line without compromising either the efficiencies or the extraction temperatures. Its use should help to better predict design efficiencies for treading, loss calculations, and equipment performance indicators.

G. E. PROCEDURES

There are two sets of turbine values which must be calculated to correctly predict a turbine heat rate. These are the turbine efficiencies and the extraction temperatures. When smooth curves are used to predict expansion lines, as with the G. E. procedures, problems arise because intermediate extraction temperatures can be as much as 14 °F above the mean turbine shell temperature.

This temperature difference is due to spill strip leakage around the end of the blades. Since extraction ports are located on the periphery of the shell, extraction flows contain a high percentage of the spill strip leakage. Since spill strip leakage does no work, extraction temperatures are always elevated. Therefore, to complete the heat balance calculation, a compromise must be made to achieve the closest match of both efficiencies and extraction temperatures.

This compromise changes the calculated last IP turbine section efficiency. According to the G.E. procedure, a smooth curve is drawn from the IP turbine bowl to the LP turbine expansion line and point (ELEP). The curve selected closely matches the extraction temperatures and yields a heat rate that is about 0.25 percent above the true design heat rate. The resultant IP turbine efficiency is lower than the true efficiency and is not constant with load.

According to the 1962 ASME paper, "A Method for Predicting the Performance of Steam Turbine Generators 16,500 KW and Larger," the IP turbine efficiency is constant throughout the load range. The constant efficiency is due to the constant pressure ratio across the IP section. Therefore, if your calculations of design IP efficiency show a change over the load range, you can be sure that the straight G. E. procedure for the entire reheat expansion line was followed. You should follow the procedures in the 1962 ASME paper for the non-condensing IP section to recalculate the proper efficiency or, remodel your PEPSE® turbine with the procedure in this paper.

In the 1962 paper, the IP efficiency from the bowl to exhaust is found on Figure 13. To use this figure the volume flow to the turbine bowl and pressure ratio across the turbine must be known. The efficiency calculated is the same for all loads. A two percent pressure loss must be accounted for from the intercept valve to the IP bowl after the efficiency is found from Figure 13.

Once the IP efficiency is found, the LP expansion line is constructed from the crossover pipe discharge to the condenser. This construction follows the same procedure as for the entire reheat expansion from the IP bowl to the LP exhaust. Typically a two percent pressure loss is expected through the crossover line.

As an example, the IP - LP extraction line was built for a 680 MW G. E. turbine with single reheat. The IP efficiency was 86.89 percent at full load with an ELEP at base pressure of 998.2 Btu/lb. The IP efficiency from Figure 13 is actually 90.91 percent. The corresponding LP turbine ELEP is 996.7 Btu/lb.

The difference between the two predictions of LP turbine ELEP probably shows the overall accuracy of the G. E. procedure. The 1.5 Btu/lb. error is 0.28 percent of the total enthalpy drop from the IP bowl to the LP turbine ELEP. It may give rise to the 0.25 percent difference in heat rate between the two methods of calculation.

PEPSE® MODELING

Two of the reasons to construct a PEPSE® model of a plant are to correctly model the as-built plant for trending analysis, and to develop realistic performance indicators. If the standard G.E. procedure is followed for the reheat turbine expansion, the IP efficiency will be slightly incorrect and performance indicators of spill strip leakage will be not be known.

Because PEPSE® is a modular code, individual turbine sections can be modeled correctly after the 1962 ASME paper. Furthermore, spill strip leakage can be represented to yield an accurate turbine model.

Word 5 of the IP turbine cards (IPTYPE) for the last reheat turbine in the cycle must be changed from 2 to 1. PEPSE® will then use the G. E. procedure for a non-condensing turbine (Figure 13) to calculate the efficiency. Also word 5 of the LP turbine cards must be changed from 3 to 2 so that PEPSE® can construct the LP expansion line. Leaving this word as 3 will result in errors in the efficiency calculation.

In addition, geometry must be added to the model to represent spill strip leakage. The suggested geometry is shown in Figure 1. This geometry has been used many times in the past and represented as an approximate solution. However, Appendix A shows a proof that this geometry correctly calculates both the extraction temperature and the turbine output power. Therefore, it is an exact mathematical solution. Because it is exact, the bypass flow calculated has physical significance and represents relative values of spill strip leakage.

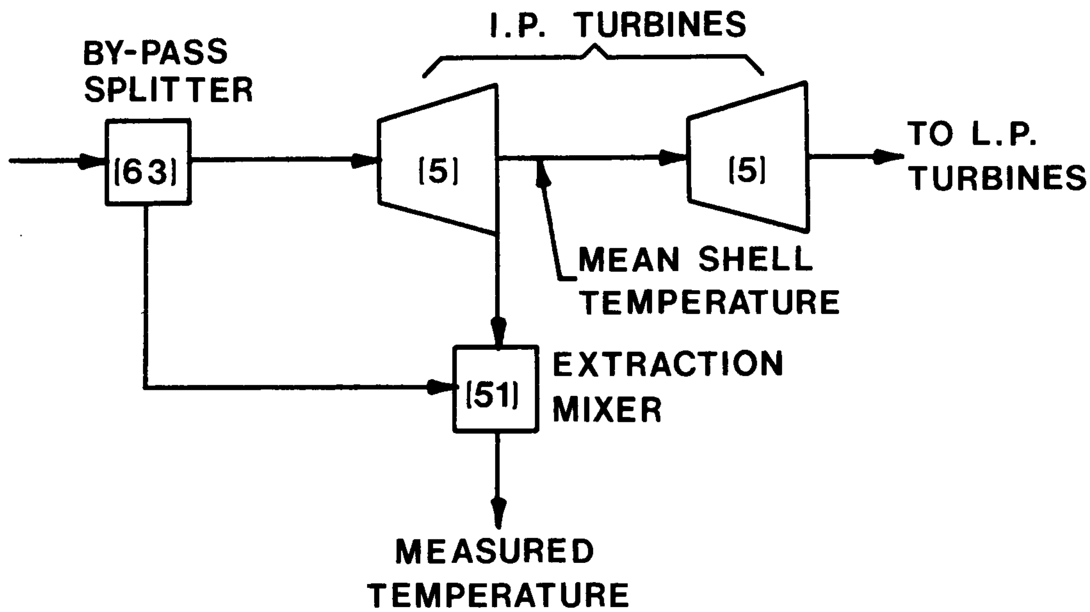

FIGURE 1. INTERMEDIATE EXTRACTION POINT GEOMETRY

In order to apply this geometry to the design or test turbine efficiency, the user must first know the elevated extraction temperature. This can be taken from: a) the G. E. heat balance; b) a PEPSE® simulation using the standard G. E. procedure with a smooth curve from the IP bowl to the LP exhaust; or c) from test data. Once this temperature is known, use a PEPSE® control to fix the bleed port flow from the by-pass splitter (shown in Figure 1) so that the elevated temperature is met at the outlet of the extraction line mixer. This should be done while the correct efficiencies are calculated.

The geometry in Figure 1 can be repeated for all intermediate extractions. Type 63 splitters are suggested because a percentage flow can be calculated at a single load and used for any load case. This prevents calculating a specific by-pass flow for every load.

Care should be exercised when calculating by-pass flows on an LP turbine with a mixture of symmetric and asymmetric extractions. Experience has shown that in these cases flow coefficients and by-pass flows for the two turbine stage groups beyond the symmetric extraction point must be equal. If they are not, PEPSE® can calculate reverse flows in one of the two symmetric extraction lines. In order to prevent this, operations shown in Appendix B should be adopted to your particular geometry. The accuracy of the reverse flow calculation is questionable; and therefore, raises concern over the procedure for the Type 52 extraction mixer. However, this topic is beyond the scope of this paper and will be left open for discussion.

During test analysis an engineer has two possible performance indicators which represent the condition of the spill strips. The first is obviously the by-pass flow calculated to yield the measured temperature. The second is the temperature difference between the turbine shell and the measured extraction. In either case, a parameter is given which can be trended and used to describe the relative condition of spill strips throughout the IP and LP turbines.

Furthermore on test data, PEPSE® will often calculate a new reference efficiency for the IP turbine. This new efficiency is due to changes in pressure ratio. This result may be used if changes in LP efficiency are known to have taken place. However, you may find the change small enough to ignore and always compare test efficiencies to the original design efficiency.

SUMMARY

A PEPSE® model has been developed which, as closely as possible, solves for the IP efficiency, LP turbine ELEP and all extraction temperatures. The results of using this model yield a performance parameter which indicates turbine seal leakage in addition to "true" turbine efficiencies. Therefore, engineers can make better comparisons of test data to design and have a better understanding of changes in turbine performance.

APPENDIX A

PURPOSE

The purpose of this appendix is to establish the accuracy of the turbine power output calculation with the PEPSE® model shown in Figure 1. In Figure 1, the by-pass split flow is calculated to yield measured or expected extraction temperatures.

DEFINITIONS

SYMBOLS

h ≡ enthalpy

m ≡ mass

P ≡ power

x ≡ blade position (fraction)

SUBSCRIPTS

b ≡ bleed

e ≡ extraction

i ≡ inlet

m ≡ mean or average value

u ≡ exhaust

1,2... ≡ turbine section

SUPERSCRIPTS

. ≡ rate

PROCEDURE

Turbine output power is calculated below for two models. The first model is the true turbine with continuous functions of enthalpy and mass flow rate versus blade position. The second model is the proposed PEPSE® model with average enthalpies for extractions and turbine exhausts.

1) True Turbine

Definitions for this section are shown in Figures A-1 thru A-3. The one assumption necessary to complete this analysis is that the mean turbine shell enthalpy, after extraction, is known. Notice in Figure A-2 that spill strip leakage causes the extraction flow to have an enthalpy higher than the mean section exhaust enthalpy.

From Figure A-3 the extraction flow rate is:

$$\dot{m}_e = \int_0^{x_e} \dot{m}(x)\, dx \qquad (1)$$

Where blade position (x) is measured as a fraction from the blade tip to the root.

The average extraction enthalpy is the enthalpy times the mass flow at each point divided by the total flow rate. That is:

$$h_e = \frac{\int_0^{x_e} h(x)\ \dot{m}(x)\ dx}{\int_0^{x_e} \dot{m}(x)\ dx} \qquad (2)$$

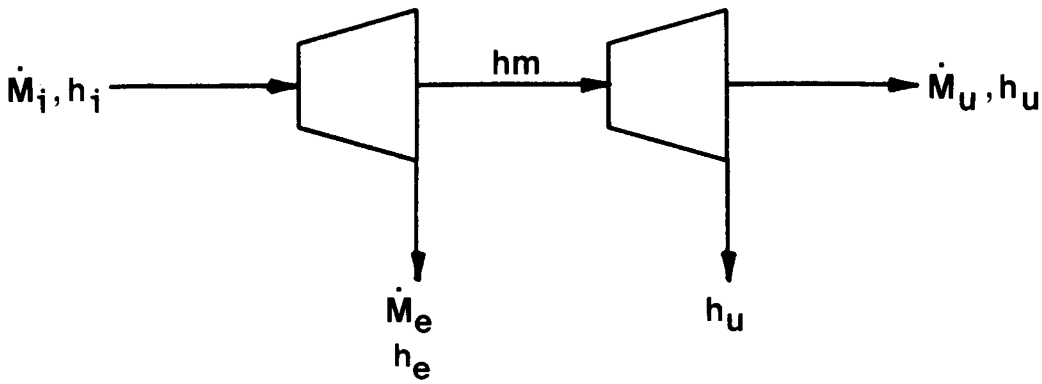

FIGURE A-1 ACTUAL TURBINE EXTRACTION GEOMETRY

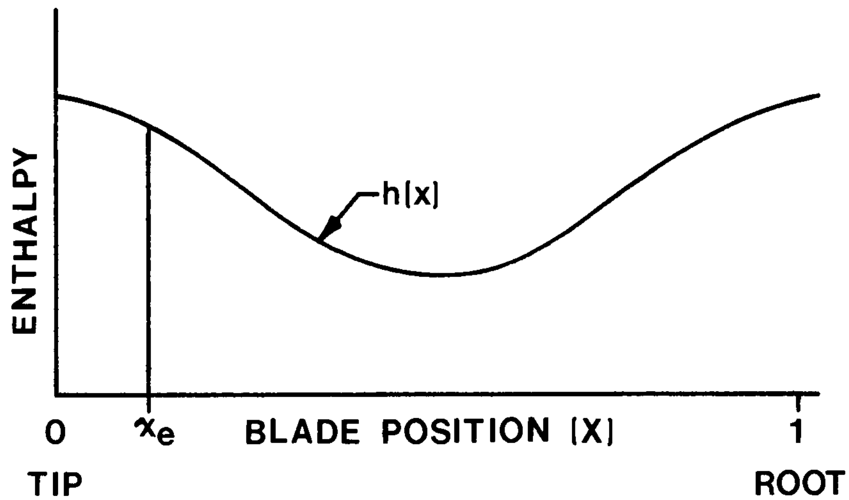

FIGURE A-2 ENTHALPY AT BLADE POSITION

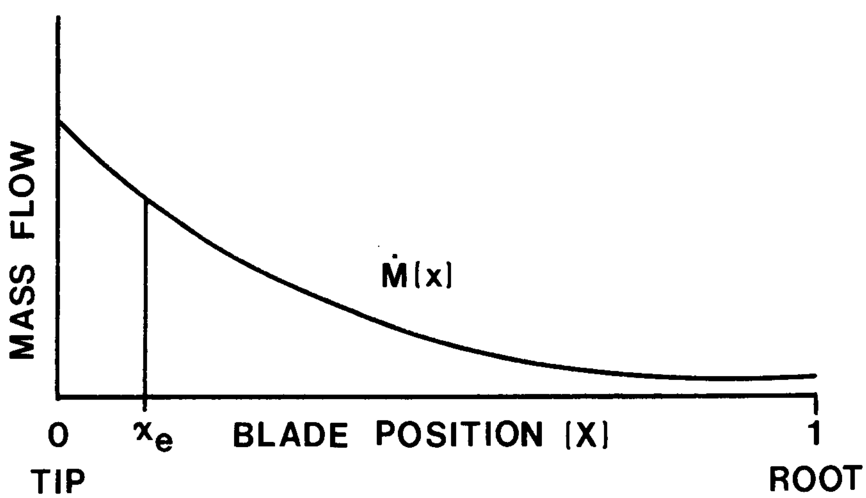

FIGURE A-3 MASS FLOW RATE AT BLADE POSITION

Similarly the average turbine exhaust enthalpy for the first section after extraction is:

$$h_m = \frac{\int_{Xe}^{1} h\,(x)\ \dot{m}(x)\ dx}{\int_{Xe}^{1} \dot{m}(x)\ dx} \tag{3}$$

The output power from the two turbine sections per pound of flow is:

$$P = h_i - \left[\int_{0}^{1} \dot{m}(x)\ h\,(x)\ dx \right] + (1-m_e) \left[h_m - h_u \right] \tag{4}$$

The integral in equation (4) can be rewritten as shown in equation (5).

$$\int_{0}^{1} \dot{m}(x)\ h\,(x)\ dx = \int_{0}^{X_e} \dot{m}(x)\ h\,(x)\ dx \qquad \int_{Xe}^{1} \dot{m}(x)\ h\,(x)\ dx \tag{5}$$

Therefore, equations (2) and (3) can be substituted into equation (4) to yield:

$$P = h_i - \left[h_e \int_{0}^{X_e} \dot{m}(x)\ dx + h_m \int_{0}^{X_e} \dot{m}(x)\ dx \right] + (1 - \dot{m}_e)(h_m - h_u) \tag{6}$$

The power output of the first turbine section only is:

$$P_1 = h_i - \left[\int_{0}^{X_e} h\,(x)\ \dot{m}(x)\ dx + \int_{Xe}^{0} h\,(x)\ \dot{m}(x)\ dx \right] \tag{7}$$

2) PEPSE® Model

The turbine power output for the PEPSE® model shown in Figure A-4 is solved for in equations (8) through (13).

From Figure A-4 the extraction enthalpy is:

$$h_e = \frac{(\dot{m}_e - \dot{m}_b)\ h_m + \dot{m}_b\ (h_i)}{\dot{m}_e} \tag{8}$$

From equation (2), the right hand side of equation (8) is:

$$\frac{(\dot{m}_e - \dot{m}_b)\ h_m + \dot{m}_b\ (h_i)}{\dot{m}_e} = \frac{\int_0^{X_e} h(x)\ \dot{m}(x)\ dx}{\dot{m}_e} \tag{9}$$

Solving for $\dot{m}_b$ in equation (9) yields:

$$\dot{m}_b = \frac{\int_0^{X_e} h(x)\ \dot{m}(x)\ dx - h_m\ \dot{m}_e}{(h_i - h_m)} \tag{10}$$

For the PEPSE® model, the turbine output power for the first turbine section is:

$$P_1 = (1 - \dot{m}_b)\ (h_i - h_m) \tag{11}$$

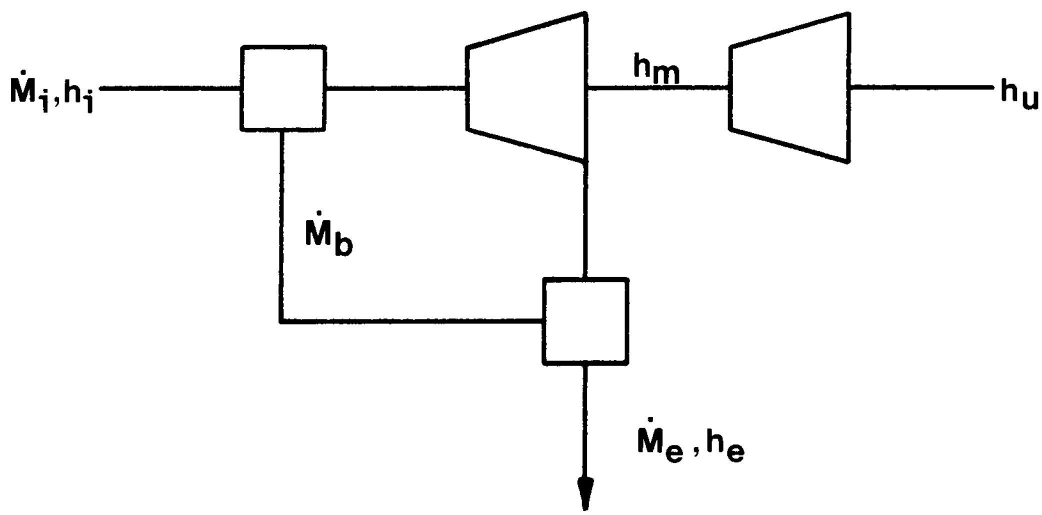

FIGURE A-4 PEPSE MODEL DEFINITIONS

Substitution of equation (9) into (10) yields:

$$P_1 = (h_i - h_m) \int_0^{x_e} h(x)\,\dot{m}(x)\,dx - h_m \dot{m}_e \qquad (12)$$

Substitution from equation (4) for h_m and simplification of (11) yields:

$$P_1 = h_i - \int_0^{x_e} h(x)\,\dot{m}(x)\,dx - \int_{x_e}^{1} h(x)\,\dot{m}(x)\,dx \qquad (13)$$

Since equations (7) and (13) are identical, the PEPSE® model solution for turbine output power is correct. Because, the solution is correct, the bleed flow (m_b) is an indication of internal turbine spill strip leakage.

APPENDIX B

For turbine geometries similar to those shown in Figure B-1, PEPSE® can often calculate negative flow rates in one of the two symmetric extraction lines. In this geometry, the two turbines have a combination of symmetric and asymmetric extractions to feedwater heaters. The negative flow generally occurs when the equivalent flow coefficients for the two stage groups beyond a symmetric extraction are not equal. This can often occur when turbine by-pass splitters are used to elevate the extraction temperature above the turbine shell temperature.

To eliminate the possibility of negative flows, use the following set of operations to properly update the demand flows from the two symmetric turbines to the feedwater heater. These equations will not change the model outcome when turbine by-pass splitters are not used.

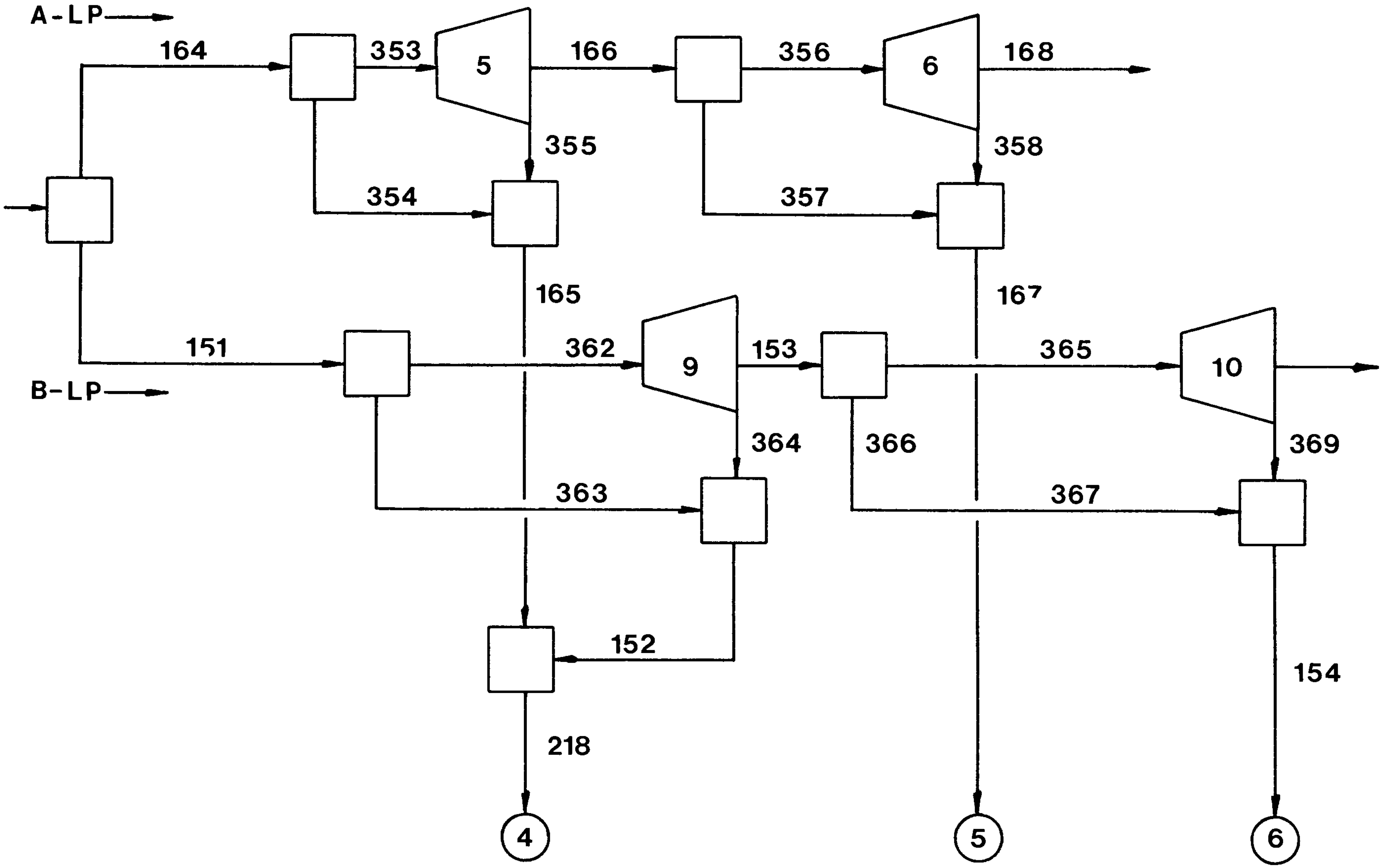
A-LP
B-LP
164
353
5
166
356
6
168
355
358
354
357
165
167
151
362
9
153
365
10
364
366
369
363
367
152
154
218
4
5
6

FIG. B-1-A

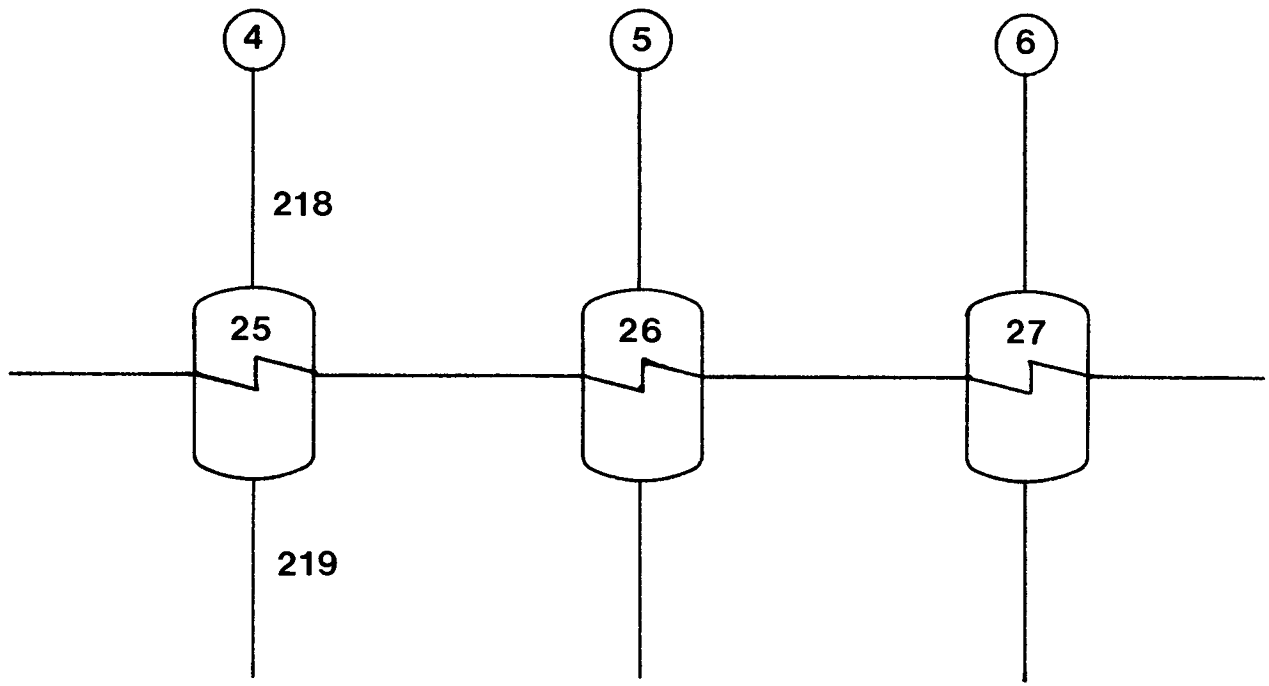

FIG. B-1-B

STEAM FLOW TO 4th POINT HEATER FROM EQUATIONS FOR TYPE 52 MIXER

870140	1.0
870180	0.5
870190	0.0

HEATER DRAIN FLOW MINUS TURBINE BLEED FLOWS

883460	WW ,	219 ,	SUB	WW ,	354 ,	OPVB, 346
883470	OPVB,	346 ,	SUB	WW ,	363 ,	OPVB, 347

EQUATION NUMERATOR

883480	OPVB,	347 ,	SUB	WW ,	164 ,	OPVB, 348
883490	OPVB,	348 ,	SUB	WW ,	151 ,	OPVB, 349

CALCULATE C^1

883500	FLOWCU ,	5 ,	DIV	FLOWCU ,	9,	OPVB, 350

CALCULATE (P/V)**0.5 FOR THE B TURBINE

883510	PP ,	153 ,	DIV	VV ,	153 ,	OPVB, 351
883520	OPVB,	351 ,	TO	OPVB,	18 ,	OPVB, 352

CALCULATE (P/V)**0.5 FOR THE A TURBINE

883530	PP , 166 ,	DIV	VV , 166 ,	OPVB, 353
883540	OPVB, 353 ,	TO	OPVB, 18 ,	OPVB, 354

CALCULATE DENOMINATOR

883550	OPVB, 352 ,	DIV	OPVB, 354 ,	OPVB, 355
883560	OPVB, 355 ,	DIV	OPVB, 350 ,	OPVB, 356
883570	OPVB, 14 ,	ADD	OPVB, 356 ,	OPVB, 357

CALCULATE FLOW FROM A LP

883580	OPVB, 349 ,	DIV	OPVB, 357 ,	OPVB, 358
883590	OPVB, 358 ,	ADD	WW, 164 ,	OPVB, 359
883600	OPVB, 359 ,	MAX	OPVB, 19 ,	OPVB, 365

CALCULATED FLOW FROM B LP

883610	OPVB, 347 ,	SUB	OPVB, 365 ,	OPVB, 366
883615 2				
*				
883630	OPVB, 19 ,	SUB	OPVB, 366 ,	OPVB, 367
883640	OPVB, 367 ,	BIF	OPVB, 19 ,	OPVB, 368
883650	OPVB, 368 ,	MUL	OPVB, 366 ,	OPVB, 369
883660	OPVB, 365 ,	ADD	OPVB, 369 ,	OPVB, 370
883670	OPVB, 347 ,	SUB	OPVB, 370 ,	OPVB, 371

RELAXATION FACTOR = 0.5

883680	WEXTP, 9 ,	SUB	OPVB,	371 ,	OPVB, 372
883690	OPVB, 372 ,	MUL	OPVB,	18 ,	OPVB, 373
883700	WEXTP, 9 ,	SUB	OPVB,	373 ,	OPVB, 376
883710	WEXTP, 5 ,	SUB	OPVB,	370 ,	OPVB, 374
883720	OPVB, 374 ,	MUL	OPVB,	18 ,	OPVB, 375
883730	WEXTP, 5 ,	SUB	OPVB,	375 ,	OPVB, 377

MAX FLOW = 200000

873780	200000.				
883800	OPVB, 376 ,	ADD	OPVB,	377 ,	OPVB, 380
883810	OPVB, 380 ,	ADD	WW,	354 ,	OPVB, 381
883820	OPVB, 381 ,	ADD	WW,	363 ,	OPVB, 382
883830	OPVB, 382 ,	MIN	OPVB,	378 ,	OPVB, 383
883840	OPVB, 383 ,	SUB	OPVB,	354 ,	OPVB, 384

MIN EXTRACTION FLOW = OPVB, 385

883850	OPVB, 384 ,	SUB	WW,	363 ,	OPVB, 385

FLOW RATIO B/(A + B)

883860	OPVB, 376 ,	DIV	OPVB, 380 ,	OPVB, 386
883870	OPVB, 386 ,	MUL	OPVB, 385 ,	OPVB, 387
883880	OPVB, 387 ,	MAX	OPVB, 18 ,	WEXTP, 9
883890	OPVB, 385 ,	SUB	WEXTP, 9 ,	OPVB, 388
883900	OPVB, 388 ,	MAX	OPVB, 18 ,	WEXTP, 5