STAG installation Free University Amsterdam

Table of Contents

5.1 Introduction

This example relates to the modelling of the combined heat and power installation of the Free University (VU) of Amsterdam, also called a mini STAG. The installation supplies heat and electricity to the University hospital. For this example, use is made of user subroutines, which also shows how the user can define his own namelists. The calculation diagram is shown in Figure 5-1.

5.2 System description

The diagram in Figure 5-1 comprises the following four cycles:

Cycle	Apparatuses	Pipes
gas turbine cycle	1- 18	1- 18
steam system	51- 62	51- 69
heating grid	101-104	101-104
cooling cycle	151-152	151-153

The combined heat and power installation is equipped with the Ruston Typhoon gas turbine, which is modelled mainly by apparatus 3 (air compressor), 5 (combustors), 7 (first stage of the expander) and 9 (second stage of the expander). The pressure drop at the inlet of the compressor is rediscounted in apparatus 2. Valve 4 separates a certain quantity of air to cool the blades of the first stage of the expander and for disc cooling. This cooling air participates in the expansion process of the second expander stage (9). The fuel for the gas turbine is Slochteren natural gas (source 16). In order to limit the NO_x production to 65 g NO_x/GJ water injection is used. In the modelling this quantity of water (from source 17) is previously mixed with the fuel at junction 18, as only two incoming lines can be connected to apparatus type 13. In apparatus 6 radiation losses are taken into account. After the expander the heat in the flue gases is transferred to the steam system (heat exchangers 11, 12 and 13) and to the heating network (heat exchanger 14).

The steam system supplies electricity and any heat for the heating network. The condensate from the condenser (51) is compressed by condensate pump 52 and pumped to the deaerator (53). The condensate is mixed with the condensate from the building heating heat exchanger 102. In the deaerator there is a steam rake, which is supplied with steam from the HP-steam turbine. Under normal conditions no steam is required for deaeration. This is possible by setting the pressure in the deaerator such that the incoming condensate (line 69) boils on its own. This pressure to be set is hence dependent on the mixture ratio between and the temperatures of the condensate streams from the condenser and the building heating heat exchanger. In the user subroutine the outlet pressure of the deaerator is set at the saturation pressure corresponding to the mixing temperature in line 69. It then follows from the calculation that the steam requirement for deaeration (line 68) is equal to zero. The steam rake comes into operation on its own where under emergency conditions the gas turbine has to be fired with oil and the inlet temperature of the feedwater in the exhaust gas boiler must be more than 100 °C.

The feedwater from the deaerator is transported by the feed pump 54 to the exhaust gas boiler. In the economizer 13 the feedwater is heated. The apparatus 12, 55 and 56 represent the evaporator with forced circulation. The steam from the drum (55) is superheated in the superheater 11. Pressure and heat losses of the live steam are rediscounted in apparatus 57. The steam expands in the HP-turbine 58 (a back pressure turbine), which drives a generator. Where there is no demand for heat, the steam can expand further in the LP-turbine 61. This LP-turbine is mounted on the same shaft as the HP-turbine. A carrier coupling makes it

possible for the LP-turbine not to be in operation and the steam from the HP-turbine can hence be fully available for heat production. It is also possible for part of the steam from the HP-turbine to be used for heat production, and for the rest to expand in the LP-turbine.
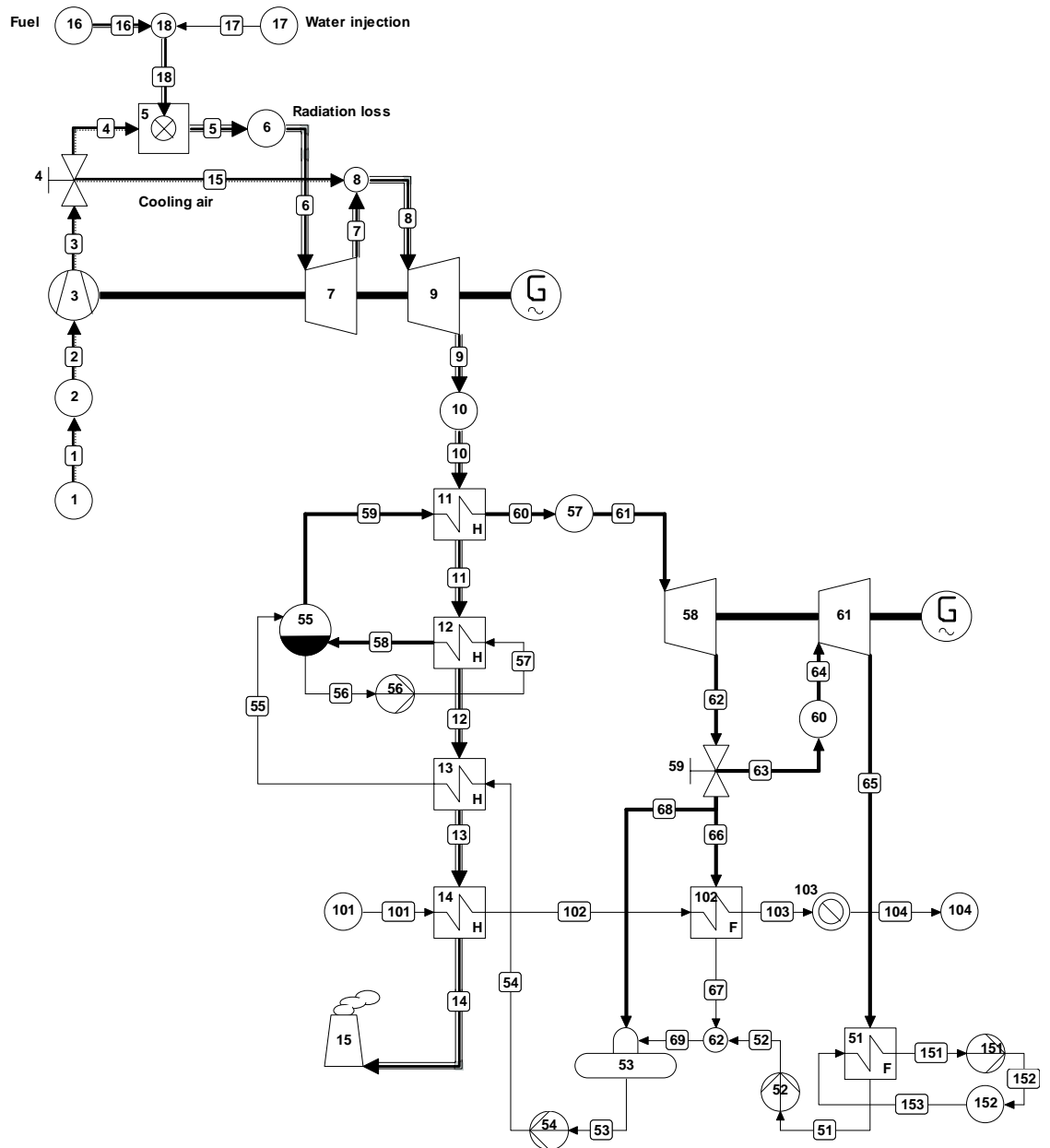

Figure 5-1: STAG installation Free University (VU) Amsterdam

The heating network is modelled in apparatus 101 to 104. The conditions in line 104 are the same as in line 101, so that the heat given off to heat sink 103 represents the total heat transfer in apparatus 14 and 102. Apparatus 103 can be understood as the heated system (the buildings).

5.3   Summary of calculations

In principle a distinction can be made between five situations:

1. Design situation: The gas turbine runs at full load, and the installation supplies the maximum electricity production.
2. The gas turbine runs at full load, and the installation supplies the maximum heat production.
3. The gas turbine runs at part load, and the installation supplies the maximum electricity production at this gas turbine load.
4. The gas turbine runs at part load, and the installation supplies the maximum heat production at this gas turbine load.
5. The gas turbine runs at part load, and the installation meets a certain heat demand.

The files representing situations 1 (example 5), 3 (example 5a), 4 (example 5b) and 5 (example 5c) are supplied with the program. The part load percentage of the gas turbine for examples 5a and 5b is 75%. For example 5c the part load percentage and the heat demand are established at 95% and 1500 kW$_{th}$ respectively.

Heat exchangers 11, 12, 13 and 51 as well as turbines 7, 9, 58 and 61 are designed for situation 1. For the other situations the design data which the program generates for this apparatuses can be used as input for off-design calculations.
Heat exchangers 14 and 102 must be designed for situation 2.
For the other three situations the design data from situations 1 and 2 can be used as input.
The user specifies the gas turbine load by the namelist CHP (= Combined Heat and Power), which is read in by user subroutine APSUB (see 5.5). In example 5c the user specifies in the same namelist how large the heat production must be. One should however take into account here that this heat production cannot be larger than the heat production in situation 4 for the same gas turbine load.

5.4 Starting points for the calculations

Here the most important starting points will suffice.

1.   Design calculation (example 5)

Gas turbine

The data relating to the gas turbine were supplied by the Dutch representative of Gowrings Continental from Maasdam. For the gas turbine the following data are used, whereby in each case an indication is given of where this is processed in the input dataset:

- ambient temperature 15 °C (TOUT for 1/10, 16/10 and 17/10)
- inlet loss 0.01 bar (DELP for 2/10)
- compression ratio 12.8:1 (processed in POUT for 3/29)
- outlet temperature compressor 367 °C (TOUT for 3/29)
- water/fuel ratio 1:2 kg/kg (DELM = -0.5, PIPE = 16 for 17/10)
- inlet temperature expander 1053 °C (TIN for 7/3)
- outlet temperature expander 508 °C (TOUT for 9/3)
- outlet loss 0.02 bar (evenly distributed via DELP1 for 11/6, 12/12, 13/6 and 14/6)
- flue gas flow rate 17,1 kg/s (converted to air flow rate DELM for 1/10)
- efficiency gear box 0.985 } both efficiencies processed in
- efficiency generator 0.97 } ETAGEN of generator 1
- fuel: Slochteren natural gas (specified for pipe 16)
- electric power 3995 kWe (follows from the calculation)

In the first instance a calculation is output, where the DELM of 1/10 is not specified and for 15/10 DELM = 17.1 is specified. From this follows an air flow rate of around 16.57 kg/s. For part load the fuel flow rate is controlled, and the air flow rate is constant. For this reason in the calculations the constant air flow rate is also assumed, specified for 1/10.

Steam system

The most important data for the steam system are:

- pressure live steam 24.1 bars (processed in turbine inlet pressure PIN for 58/3)

- temperature live steam 287 °C (TOUT1 for 11/6)

- pressure drop live steam 0.3 bar (DELP for 57/10)

- heat loss live steam 1 kJ/kg (DELH for 57/10)

- isentropic efficiency back pressure turbine 0.665 (ETHAI for 58/3)

- outlet pressure back pressure turbine 3.6 bar (processed in PIN2 for 102/5)

- isentropic efficiency condensation turbine 0.55 (ETHAI for 61/3)

- condenser pressure 0.2 bar (processed in PINL as extra condition for pipe 65)

- pinch-point temperature difference 10 °C (DELTL for 12/12)

- approach temperature difference around 5 °C (processed in TOUT1 for 13/6)

For the heat exchangers in the heating network (14/6 and 102/5) the outlet temperatures of the heating water (TOUT1) are specified. Via valve 59/14 it is specified that no steam goes to heat exchanger 102/5. From the energy balance over apparatus 102/5 a mass flow of heating water is then calculated equal to zero. From the energy balance over apparatus 14/6 it then naturally follows that the inlet temperature of the flue gases is equal to the outlet temperature.

The specification for valve 59/14 thus ensures that the situation of maximum electricity production is calculated.

2.   Maximum heat production (gas turbine at full load)

No calculation example of this situation is included. The differences with regard to the design calculation are:

- for the apparatus 11/6, 12/12, 13/6, 51/5, 58/3 and 61/3 the design data (which are generated by the design calculation) are included as off-design input data for the relevant apparatuses)

- outlet temperature heating water building heating boiler bundle 97 °C (TOUT1 for 14/6)

- outlet temperature heating water building heating heat exchanger 134 °C (TOUT1 for 14/6)

- return temperature heating water 90 °C (TOUT for 101/10)

- no steam through condensation turbine (RMASS1 = 0.0 for 59/14)

3.   Maximum electricity production (gas turbine on part load) (example 5a)

The design data for heat exchangers 14/16 and 102/5, generated by running situation 2, are imported as off-design input data. The design data for expanders 7/3 and 9/3 are imported also. The design data for apparatuses 14/6 and 102/5 are not added, as the installation in this situation does not produce any heat. This results in 8 apparatuses operating in off-design mode. A little information on the use of the part load data is appropriate here.

The design data of heat exchangers can be used by the program to calculate a temperature or a temperature difference in off-design situations.
Where the design data of a heat exchanger contains the UA-value for the design situation, then the procedure is that the user omits a temperature specification for the relevant apparatus. This results in the following:

    11/6   TOUT1 omitted
    12/12   DELTL omitted
    13/6   TOUT1 omitted

Where the design data of a heat exchanger contains no UA-value (this is the case for apparatuses of type 5, which is used here for modelling the condenser), then the program alters the temperature difference (DELTH of DELTL) specified for the design situation on the basis of the actual mass flow rates. This design value of the temperature difference must remain as input for the relevant apparatus. To be able to process this procedure, the DELT1 for 51/5 in the design calculation is replaced by a DELTH = 5.0 K corresponding fully to this. Also for the off-design situation for apparatus 51/5 the input parameter DELTH is then kept. The program will use this value to determine a DELTH valid for the present situation (see Figure 2-3 in paragraph 2.6 of part "Reference Guide" of the manual).

The design data of the expanders and turbines in the system can be used by the program to calculate new inlet and extraction pressures on the basis of Traupel's formula. This means that the user ensures that these pressures are not already established by input data. Also the user must check how far in the design calculation other specified input data must be omitted. The outlet temperature of the gas turbine for example is not constant; this means that in concrete terms for 9/3 TOUT must be omitted. As the air flow rate is constant, it is assumed that the isentropic efficiencies of the compressor and the two expanders are constant. These

isentropic efficiencies are, where they are not specified, calculated by the program in the design situation (see example 5). For this example this results in the following:

3/29	POUT omitted
	TOUT replaced by ETHAI
7/3	TIN omitted (see below)
9/3	PIN omitted
	TOUT replaced by ETHAI
58/3	PIN omitted

Finally it can also be indicated that valve 59/14 ensures that no steam goes in the direction of the building heating heat exchanger 102/5.

The user can specify in namelist &CHP what the part load percentage of the gas turbine must be. This part load percentage is converted to a mass flow of fuel. The fuel flow is therefore specified for 16/10. As the fuel stream is now known, for 5/13 the EEQCOD must be changed to 2 to calculate the outlet temperature. In order to leave this outlet temperature unknown, TIN must be omitted for 7/3. 5.5 deals with namelist &CHP.

4. Maximum heat production (gas turbine on part load) (example 5b)

The input dataset for example 5b shows a lot of similarity with the one dealt with above. The design data for heat exchangers 14/6 and 102/5 are added. The input data for these apparatuses are altered as follows:

14/6	TOUT1 omitted
102/5	Unchanged; the specified DELTL (valid for situation 2) is altered by the program.

Valve 59/14 now blocks the steam supply to the condensation turbine 61/3.
The user can again specify in namelist &CHP the part load percentage of the gas turbine.

5.   Specified heat demand (gas turbine on part load) (example 5c)

The input data for example 5c correspond very much to that in example 5b. In addition to the part load percentage the user can specify how large the heat demand which the installation must meet is in kW$_{th}$. This heat demand does in fact determine the mass flow in the heating network. For this reason for apparatus 101/10 the mass flow is specified which is then altered in accordance with the heat demand specified. The quantity of steam necessary for this heat demand can be calculated from the energy balance of apparatus 102/5. The rest of the steam will expand in the condensation turbine. It is then no longer necessary to determine the mass flow by means of valve 59, but to let it be calculated by the program itself. Valve 59/14 is therefore replaced by fork 59/9. The translation of the specified heat demand into the heating water flow rate is further explained in 5.5.

5.5   Use of user subroutine APSUB

For modelling the behaviour of the combined heat and power/power installation the facilities of the routine APSUB is used. In short the use of this routine can be described in this example:

- determination and control of the mass flow of fuel so that the specified part load percentage is reached;
- determination and control of the deaerator pressure so that no steam supply is necessary;
- determination and control of the water flow rate in the heating network so that the specified heat demand is met.

Subroutine APSUB is called for each apparatus which is specified at Calculation | User Subroutines in the row of apparatus numbers, in the order of the input.

In the declarations there is a namelist declaration. The namelist &CHP may contain the variables GTLOAD (the part load percentage of the gas turbine) and HEATPR (the heat production of the combined heat and power installation). The user adds this namelist to the input dataset. The namelist is read in by subroutine APSUB in the zeroth main iteration of the calculation process.

For the input variables GTLOAD and HEATPR a few mass flows specified in the input dataset must be altered. This relates to the specified mass flows for fuel for 16/10 and heating water for 101/10. The program does not have the facility to alter the input parameter DELM of apparatus type 10 where this is specified as an absolute mass flow. It is possible to alter the mass flow where this is specified relative to another mass flow in the system. As the air flow rate is constant at all times, the mass flows to be altered may then be related to the air flow rate, which enters the system via source 1/10.

As the mass flows to be altered are related to the mass flow of air in line 1, this air flow rate must be established in a variable. In the first main iteration the mass flow for the outlet line of apparatus 1 is allocated to the variable FMAIR (kg/s). As subroutine APSUB is then left and only later called for the next apparatus specified at Calculation | User Subroutines, variable FMAIR must be saved. This is the function of the SAVE statement: variable FMAIR is declared in the SAVE statement, so that in a subsequent call of subroutine APSUB the numerical value of variable FMAIR is still known. This also applies for the other variables, which are specified in the SAVE statement.

For part load operation of the gas turbine, the fuel input is controlled; the air delivery of the compressor is constant (there is no control by means of the adjustable blades). The part load operation relates to situations 3, 4 and 5 (see 5.3). For these situations the mass flow of fuel is specified for apparatus 16/10. The purpose is to adjust the specified mass flow such that the electric power of the gas turbine corresponds to the specified part load percentage (electric power of the gas turbine expressed in percent of the full load power). The mass flow of fuel is for 16/10 specified relative to the mass flow in line 1. This then offers the possibility of adjusting this input data in subroutine APSUB.

In general with part load operation the efficiency of a gas turbine will fall. This means that with a part load percentage of X% the fuel input will be more than X% of the fuel input at full load.   It has hence been found that in this case for a part load percentage of 75% the fuel input will be around 78% of the fuel input at full load. A second point is determined in the same way for a full load percentage of 95%. A straight line is drawn through the points found for the relation between the fuel flow rate and the part load percentage, which is programmed in APSUB. In this way within certain limits the fuel flow can be determined using the part load percentage GTLOAD. For apparatus type 10 the parameter DELM is in memory place 8 in array DATA (see part "User Subroutines" of the manual). In the statement starting with DATA (8) the adjustment of DELM is thus carried out.

The value of the mass flow of fuel applicable in the present main iteration is both written to screen and to the output file.

For apparatus 53 the input parameter POUT must be altered. This parameter is stored in DATA (2) for apparatus type 7. First one finds out what the internal line number is for line 69 (see calculation diagram). This internal line number is stored under the name LCOND. In a simple way in array T the temperature in line 69 can be found. This is written both on the screen and in the output file. Routine PTXW (see part "User Subroutines" of the manual) is used to determine the saturation pressure of water PSAT at this temperature. This value is then allocated to DATA (2) or POUT of apparatus 53. In addition a stability criterion is built in here. The deaerator pressure is minimal, the condenser pressure (0.2 bar). During the iteration process negative temperatures can be calculated. Where this is the case, the deaerator pressure is not calculated but set at 0.2 bar. The saturation pressure is again shown on the screen and in the output file.

The heat production of the installation is equal to the heat which disappears in sink 103/10. The incoming enthalpy (line 103) is allocated to variable HMAX, the outgoing enthalpy (line 104) to variable HMIN. Where now the specified heat production HEATPR is divided by the difference between HMAX and HMIN, the water flow rate in the heating network is obtained. For apparatus 101 parameter DELM is altered in this way. The role of variable FMAIR in this has already been explained above.

5.6   Source text of user subroutine APSUB

```
*-----------------------------------------------------------------------*
*      User subroutine APSUB, meant for ex5-ex5c                        *
*                                                                       *
*      Mini-STAG VU-Amsterdam                                           *
*-----------------------------------------------------------------------*

      SUBROUTINE APSUB( NLIN,ILIN,IAP,ITYP,ITM,DATA,NP,IPIPE,FM,H,
     *                  P,T,X,C,RESULT,COMP,CONC,AVERG,IDX,NCOMP,APNAME,
     *                  NUMGEN,RDATGE)

      IMPLICIT DOUBLE PRECISION (A-H,O-Z)

      DOUBLE PRECISION  DATA(50),FM(NP),H(NP,3),P(NP,3),T(NP,2),
     *                  X(NP,2),C(NP),CONC(NLIN+7,NCOMP),AVERG(NLIN+7),
```

```
      *                      RDATGE(NUMGEN,6)
       INTEGER              IPIPE(NP),ILIN(NLIN),IDX(NCOMP)
       CHARACTER            COMP(NCOMP)*8,APNAME*12



       NAMELIST /CHP/ GTLOAD, HEATPR
       SAVE GTLOAD, HEATPR, FMAIR, LCOND, LIN, LOUT, HMAX, HMIN


*-----------------------------------------------------------------------------*
*     Read namelist &CHP only in iteration number zero                        *
*-----------------------------------------------------------------------------*

       IF (ITM.EQ.0) THEN

          REWIND 9
          READ(9,CHP,END=1)
    1     CONTINUE

*         Save air mass flow of apparatus 1
          IF (IAP.EQ.1) FMAIR=FM(1)

       ENDIF



*-----------------------------------------------------------------------------*
*     Calculate fuel mass flow ( DELM <==> DATA(8) ) of source 16             *
*-----------------------------------------------------------------------------*

       IF (IAP.EQ.16) THEN

          DATA(8)=-1.0*(0.007472484*GTLOAD+0.25267991)*0.3682923/FMAIR

          WRITE(6,100) IAP
          WRITE(6,110) -1.0*DATA(8)*FMAIR

          WRITE(7,100) IAP
          WRITE(7,110) -1.0*DATA(8)*FMAIR

  110     FORMAT(' Current fuel mass flow is         ',F6.2,' kg/s')

       ENDIF
```

```
*------------------------------------------------------------------------*
*     Equalize the deaerator outlet pressure ( POUT <==> DATA(2) )       *
*     to the saturation pressure at prevailing temperature               *
*------------------------------------------------------------------------*

      IF (IAP.EQ.53) THEN

*        Find internal number of deaerator outlet pipe
         IF (ITM.EQ.0) THEN
            DO 10 I=1,NP
               IF (ILIN(IPIPE(I)).EQ.69) LCOND=I
   10       CONTINUE
         ENDIF

*        Calculate saturation pressure
         IF (T(LCOND,1).GT.0.0) THEN
            W = 1
            PSAT = PTXW(T(LCOND,1),X,W,C,LCOND)
            DATA(2)=PSAT
         ELSE
            PSAT=0.2
            DATA(2)=PSAT
         ENDIF




*        Write results to screen
         WRITE(6,100) IAP
         WRITE(6,120) T(LCOND,1)
         WRITE(6,121) PSAT

*        Write results to standard output file
         WRITE(7,100) IAP
         WRITE(7,120) T(LCOND,1)
         WRITE(7,121) PSAT

  120    FORMAT(' Current condensate temperature is ',F6.2,' øC')
  121    FORMAT(' Current saturation pressure is    ',F6.2,' bar')

      ENDIF
```

```
*-----------------------------------------------------------------------*
*     Calculate mass flow ( DELM <==> DATA(8) ) of source 101          *
*-----------------------------------------------------------------------*

      IF (IAP.EQ.101) THEN

         DATA(8)=-1.0*(HEATPR/(HMAX-HMIN))/FMAIR

*        Write results to screen
         WRITE(6,100) IAP
         WRITE(6,130) -1.0*DATA(8)*FMAIR

*        Write results to standard output file
         WRITE(7,100) IAP
         WRITE(7,130) -1.0*DATA(8)*FMAIR

  130    FORMAT(' Current mass flow heating grid is ',F6.2,' kg/s')

      ENDIF

*-----------------------------------------------------------------------*
*     Calculate enthalpies at in- and outlet of apparatus 103          *
*-----------------------------------------------------------------------*

      IF ((IAP.EQ.103).AND.(ITM.LE.2)) THEN

*        Find internal number of in- en outletpipe of apparatus 103
         DO 20 I=1,NP
            IF (ILIN(IPIPE(I)).EQ.103) LIN=I
            IF (ILIN(IPIPE(I)).EQ.104) LOUT=I
  20     CONTINUE

         HMAX=H(LIN,2)
         HMIN=H(LOUT,1)

      ENDIF

  100 FORMAT(/ '  ----- Apparatus',I4,' ------------------------')

*-----------------------------------------------------------------------*
      END
*-----------------------------------------------------------------------*
```