

Estimation of Process Side Thermal Efficiency of Fired Heaters

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Fired Heaters are the major energy consumers in refinery and petrochemical plants. The initiative to ensure that these heaters run close to their design efficiency is tremendous. Heater operating efficiency is an estimation of the net heat being transferred from fuel oil / gas to the process fluid. The present paper focuses on the development of a computer package for calculation of process side thermal efficiency. The results of the efficiency calculations have been reported for a typical crude furnace. The same are compared against DESIGN-II process simulator calculations and have been found to be within $\pm 5\%$ error.

The above program is based on semiempirical approach and can be used for estimating the absorbed duty without detailed investigation on the flue gas side. It can also generate the TBP curve based on the temperature, pressure and absorbed duty.

Fired heaters are the major energy consumers in the refinery and petrochemical plants and efforts are being made to optimize the same. Heater efficiency calculations conventionally involve the estimation of heat losses from the heater to the ambient (shell loss) and sensible heat loss through flue gas, which are inferred from the measurement of furnace shell temperature, stack temperature, excess air, etc. The above is a time consuming process since lots of data are to be collected. However, an alternative approach for heater efficiency estimation involves the calculation of the net heat absorbed by the process fluid (absorbed duty). The present paper focuses on the development of a computer package for the same.

Objective

The main objective of the software is to calculate the absorbed duty of the heater based on process side parameters like flow, temperature, pressure and TBP analysis. This procedure would enable a crosscheck of the efficiency calculated from the flue gas side (indirect method).

There are cases where TBP of the process fluid is not available. The same is found with information available on pressure, temperature of process side and absorbed duty calculated from indirect method.

Procedure for Petroleum Fraction Enthalpy Calculation

The computer package developed is primarily based on *American Petroleum Institute (API) Technical Data Book*

— *Petroleum Refining* (1980)[1]. Entire calculation procedure is described in following steps:

1. Splitting Data into Pseudocomponents

The given True Boiling Point curve (TBP vs. wt %) is split into 5 - 25° C so cut that each cut lies on a linear segment of the TBP curve. The mid-point of each segment represents the True Average Boiling Point (TAVBP) of each pseudocomponent. Actual weight percent of each pseudocomponent is the difference between cumulative weight percent corresponding to the final and initial boiling point of each linear segment.

2. Calculation of Thermo-Physical Properties:

Following Thermo-Physical parameters are calculated by using API procedures:

(a) Watson Coefficient, K:

It is defined as [1]:

$$K = \frac{\left[\sum_{i=1}^n T_{b_i} \cdot x_{w_i} \right]^{\frac{1}{3}}}{S}$$

Here an assumption is made that Weight Average Boiling Point (WABP), Volume Average Boiling Point (VABP) and 50% boiling point (ASTM D-86) of crude petroleum is approximately the same [2].

(b) Specific Gravity, Molecular weight, Pseudocritical temperature and pressure are calculated as below. [1]

$$S_i = \frac{[T_{b_i}]^{\frac{1}{3}}}{K}$$

$$M_i = 2.0438 \times 10^2 \exp(0.00218 T_{b_i}) \exp(-3.07S) T_{b_i}^{0.118} S^{1.88}$$

$$T_{c_i} = 24.2787 T_{b_i}^{0.58848} S_i^{0.3596}$$

$$P_{c_i} = 3.12281 \times 10^9 T_{b_i}^{-2.3125} S_i^{2.3201}$$

(c). Vapour Pressure:

Vapour pressure of each pseudocomponent at $T_{r,i}=0.7$ is calculated by the following procedure: [1]

- Calculate Watson Coefficient, K and true average boiling point, T_{b_i}
- Set $T_{b_i} = T_{b_i}$ and $T = 0.7 T_{c_i}$, and calculate vapour pressure P_i^* (mm Hg)

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$$X_i = \frac{T^* b_i - 0.0002867 T^* b_i}{748.1 - 0.2145 T^* b_i}$$

$$\log P_i^* = \frac{3000.538 X_i - 6.761560}{43 X_i - 0.987672} \text{ for } X_i > 0.0022 (P_i^* < 2 \text{ mm Hg})$$

iii. Calculate K correction factor:

$$\Delta T_i = 2.5 f (K-12) \log (P_i^*/760)$$

Where, correction factor is defined:

$$f = 1 \text{ for } T_{b_i} > 400 \text{ F}$$

$$f = 0 \text{ for } T_{b_i} < 200 \text{ F}$$

$$f = (T_{b_i} - 659.7)/200 \text{ for } 200 < T_{b_i} < 400$$

$$\log P_i^* = \frac{2663.129 X_i - 5.994296}{95.76 X_i - 0.972546}$$

for $0.0013 \leq X_i \leq 0.0022$ ($2 \text{ mm Hg} \leq P_i^* < 760 \text{ mm Hg}$)

$$\log P_i^* = \frac{2770.085 X_i - 6.412631}{36 X_i - 0.989679} \text{ for } X_i < 0.0013 (P_i^* > 760 \text{ mm Hg})$$

iv. Now set:

$$T^* b_i = T^* b_i - \Delta T$$

And repeat step 2 & 3, till vapour pressures calculated from subsequent steps do not change significantly.

(g). Acentric factor:

Acentric factor of pseudocomponent is calculated by following equations [1]

$$\omega_i = -\log (P_i^*/P_{c_i}) - 1.00 \quad (T_{r,i}=0.7)$$

Calculation of Ideal Gas Enthalpy of Individual Pseudocomponent:

The following equations are used for estimating the ideal gas enthalpy of each pseudocomponent: [1]

Region- I:

Liquid phase where $T_{r,i} \leq 0.8$ and $P_{r,i} \leq 1.0$, the equation is:

$$H_{l,i} = A_1 [T - 259.7] + A_2 [T^2 - 259.7^2] + A_3 [T^3 - 259.7^3]$$

Where:

$$A_1 = 10^{-3} \left[-1171.26 + (23.722 + 24.907 S_i) K + \frac{(1149.82 - 46.535 K)}{S_i} \right]$$

$$A_2 = 10^{-6} \left[(1.0 + 0.82463 K) \left\{ 56.086 - \frac{13.817}{S_i} \right\} \right]$$

$$A_3 = 10^{-9} \left[(1.0 + 0.82463 K) \left\{ 9.6757 - \frac{2.3653}{S_i} \right\} \right]$$

Region- II

Vapour phase or liquid phase with $T_{r,i} > .8$ or $P_{r,i} > 1.0$, the equation is:

$$H_i = H_{L,i} + B_1 [T - 0.8 T_{c,i}] + B_2 [T^2 - 0.64 (T_{c,i})^2] + B_3 [T^3 - 0.512 (T_{c,i})^3] + \frac{R T_{c,i}}{M_i} [4.507 + 5.266 \omega_i - \left(\frac{H^0 - H_i}{RT_{c,i}} \right)]$$

Where:

$$B_1 = 10^{-3} \left[-356.44 + 29.72 K + B_4 \left(295.02 - \frac{248.46}{S_i} \right) \right]$$

$$B_2 = 10^{-6} \left[-146.24 + (77.62 - 2.722 K) K - B_4 \left(301.42 - \frac{253.87}{S_i} \right) \right]$$

$$B_3 = 10^{-9} [-56.487 - 2.95 B_4]$$

$$B_4 = \left[\left(\frac{12.8}{K} - 1.0 \right) \left(1.0 - \frac{10.0}{K} \right) (S_i - 0.885)(S_i - 0.70) 10^4 \right]^2$$

for $10.0 < K < 12.8$ with $0.70 < S_i < 0.885$

$B_4 = 0$ for all other cases.

Calculation of Enthalpy Pressure Correction Term:

The following correlations are used for calculating the pressure effect on the enthalpy of individual pseudocomponent [1]:

Pitzer's Generalized virial equation:

Excess enthalpy for $0 \leq P_{r,i} \leq 0.2$

$$\left(\frac{H^0 - H_i}{RT_{c,i}} \right) = -P_{r,i} [(0.1445 + 0.073 \omega_i) - (0.660 - 0.92 \omega_i) T_{r,i}^{-1} - (0.4155 + 1.5 \omega_i) T_{r,i}^{-2} - (0.0484 + 388 \omega_i) T_{r,i}^{-3} - (0.0657 \omega_i T_{r,i}^{-8})]$$

For $P_{r,i} > 0.2$ following general equation is used:

$$\left(\frac{H^0 - H_i}{RT_{c,i}} \right) = \left(\frac{H^0 - H_i}{RT_{c,u}} \right)^{sm} + \frac{\omega_i}{\omega_i^{sm}} \left[\left(\frac{H^0 - H_i}{RT_{c,s}} \right)^{sm} - \left(\frac{H^0 - H_i}{RT_{c,u}} \right)^{sm} \right]$$

Dimensionless effects of pressure on the enthalpies of pseudo component and heavy reference fluid are to be calculated from the following equations:

$$\left(\frac{H^0 - H_i}{RT_{c,i}} \right)^{(i)} = -T_{r,i} \left\{ z^{(i)} - 1 - \frac{b_2 + \frac{2b_3}{T_{r,i}} + \frac{3b_4}{T_{r,i}^2}}{T_{r,i} V_{r,i}} - \frac{c_2 - \frac{3c_3}{T_{r,i}^2}}{2 T_{r,i} V_{r,i}^2} + \frac{d_2}{5 T_{r,i} V_{r,i}^5} + 3E \right\}$$

$$E = \frac{c_4}{2 T_{r,i}^2 \gamma} \left\{ \beta + 1 - \left(\beta + 1 + \frac{\gamma}{V_{r,i}^2} \right) \exp \left(-\frac{\gamma}{V_{r,i}^2} \right) \right\}$$

Where:

$b_2, b_3, b_4, c_2, c_3, c_4, d_2, \gamma$ and β are two sets of constants, one set for the simple fluid and another for the heavy reference fluid.

Calculation of Density of Pure Hydrocarbon & Nonpolar Gases:

The following expressions are used for estimating the density of pseudo component [1]:

$$z_i = z^{(o)} + \frac{\omega_i}{\omega^{(h)}} (z^{(h)} - z^{(o)})$$

The compressibility factors for the simple fluid $z^{(o)}$ and the heavy fluid $z^{(h)}$ are obtained from the following equation:

$$z^{(o)} = \frac{P_{r,i} V_{r,i}}{RT_{r,i}} = 1 + \frac{B}{V_{r,i}} + \frac{C}{V_{r,i}^2} + \frac{D}{V_{r,i}^3} + \frac{c_4}{T_{r,i}^3 V_{r,i}^2} \left(\beta + \frac{\gamma}{V_{r,i}^2} \right) \exp \left(\frac{-\gamma}{V_{r,i}^2} \right)$$

Where:

$$B = b_1 - \frac{b_2}{T_{r,i}} - \frac{b_3}{T_{r,i}^2} - \frac{b_4}{T_{r,i}^3}$$

$$C = c_1 - \frac{c_2}{T_{r,i}} + \frac{c_3}{T_{r,i}^3}$$

$$D = d_1 + \frac{d_2}{T_{r,i}}$$

R = gas constant = 10.731 psia.ft³/ (lb-mole) Two sets of constants are given in [1].

Calculation of Overall Enthalpy of Crude Petroleum [2] :

Ideal gas enthalpies of individual pseudocomponent are summed up on weight average basis to calculate the overall ideal gas enthalpy of crude petroleum.

$$H_p^0 = \sum_{i=1}^n x_{wi} H_i$$

Overall critical temperature, critical pressure, molecular weight, acentric factor of crude petroleum is calculated on a molar average basis as below.

$$Tc_p = \sum_{i=1}^n x_{mi} Tc_i$$

$$Pc_p = \sum_{i=1}^n x_{mi} Pc_i$$

$$\omega_p = \sum_{i=1}^n x_{mi} \omega_i$$

$$M_p = \sum_{i=1}^n x_{mi} M_i$$

The pressure correction term is calculated for overall crude petroleum on the basis of molar average properties, Tc_p , Pc_p , ω_p .

The total enthalpy of crude petroleum is calculated from the following equation:

$$H_p = H_p^0 - \frac{RTc_p}{M_p} \left(\frac{H^0 - \bar{H}}{RTc_p} \right)$$

Results and Discussion

A software based on semi-empirical equations has been developed for estimation of process side absorbed duty of refinery heaters. Runs are taken to estimate the absorbed duty at various temperatures and pressure and the same are compared with the enthalpy calculated by Design-II. A comparison of the Program with Design II simulation at various pressures is shown in Fig-1. It is observed that as the pressure increases, the enthalpy difference decreases. This is attributed to the difference in vaporisation, predicted by Design - II.

However, for all the cases, the maximum deviation of enthalpy calculation from Design-II is within 5%.

The above program has modules, which on the basis of the process parameters like pressure, temperature and absorbed duty, generates the TBP curve and this is done using a multivariable search for the coefficients of the

TBP curve. The above can be a useful tool when simulating crude switchover where the composition of crude is constantly changing.

Conclusions

A computer package for the calculation of absorbed duty and process side efficiency of process heaters has been developed. The program is useful in studying the operation of heater and improving its performance. The package can be used for process side calculations of heaters for estimating the COT/COP, absorbed duty, etc. Based on the available furnace operating data, the package can also be used for predicting TBP of the process fluid before entering the distillation column. This can be used in the optimisation of column operation.

References

1. API Division of Refining, *Technical Data Book- Petroleum Refining*, 1980.
2. Huang, P.K., and Daubert Thomas, E.: Prediction of the Enthalpy of Petroleum Fractions. The Pseudocompound Method, *Ind. Eng. Chem., Process Des. Dev.*, 13, 359(1974)

Nomenclature

- H_p^0 = Ideal gas enthalpy of crude petroleum, BTU/lb.
 H_{inlet}^0 = Enthalpy of process fluid at the furnace inlet, Kcal/Kg.
 H_{outlet}^0 = Enthalpy of process fluid at the furnace outlet, Kcal/Kg.
 $H_{l,s}$ = Enthalpy of pseudocomponent in liquid phase (Region-I), BTU/lb.
 $H_{l,r}$ = Enthalpy of pseudocomponent in liquid phase (Region-I) at a reduced temperature of 0.8, BTU/lb.
 H_i = Enthalpy of pseudocomponent in liquid/ vapour phase (Region - II), BTU/lb.
K = Watson characterization factor of crude petroleum
 LHV_{fuel} = Lower heating value of fuel oil + Gas mixture, Kcal/Kg.
 M_i = Molecular weight of pseudocomponent.
 m_{crude} = Mass flow rate of crude (process fluid), Kg/hr
 m_{fuel} = Mass flow rate of fuel (oil + gas), Kg/hr
n = no. of pseudocomponents.
P = Pressure, psia.
 P_i^* = Vapour pressure of pseudocomponent, mm Hg
 P_c = Pseudocritical pressure of crude petroleum.
 $P_{c,i}$ = Pseudocritical pressure, pounds per square inch absolute
 $P_{r,i}$ = Reduced pressure of pseudocomponent. = $P/P_{c,i}$
R = Gas constant, 1.986 BTU/lb.-mole-°R
S = Overall standard specific gravity of crude petroleum.
 S_i = Standard specific gravity of pseudocomponent.
T = Temperature, °R
 Tb_i = True average boiling point of pseudocomponent.
 T_c = Pseudocritical temperature of crude petroleum, °R
 $T_{c,i}$ = Pseudocritical temperature of pseudocomponent, °R
 $T_{r,i}$ = Reduced temperature of pseudocomponent = $T/T_{c,i}$
 $V_{r,i}$ = Reduced volume of pseudocomponent, $P_{c,i}V/R.T_{c,i}$
 $x_{w,i}$ = Weight fraction of each pseudocomponent
 $x_{m,i}$ = Molar fraction of individual pseudocomponent.
 $z^{(j)}$ = Compressibility factor of the simple fluid/ heavy reference fluid.
 z_i = Compressibility factor for pseudocomponent, dimensionless

Greek Letters:

- η = Operating efficiency of the furnace
 ω_i = Acentric factor of pseudocomponent
 ω_p = Acentric factor of crude petroleum.
 $\omega^{(h)}$ = Acentric factor of heavy reference fluid, n-octane = 0.3978

Subscript:

- i = Pseudocomponent
p = Crude petroleum

Superscript

- j = 0, for simple fluid
h, for heavy reference fluid

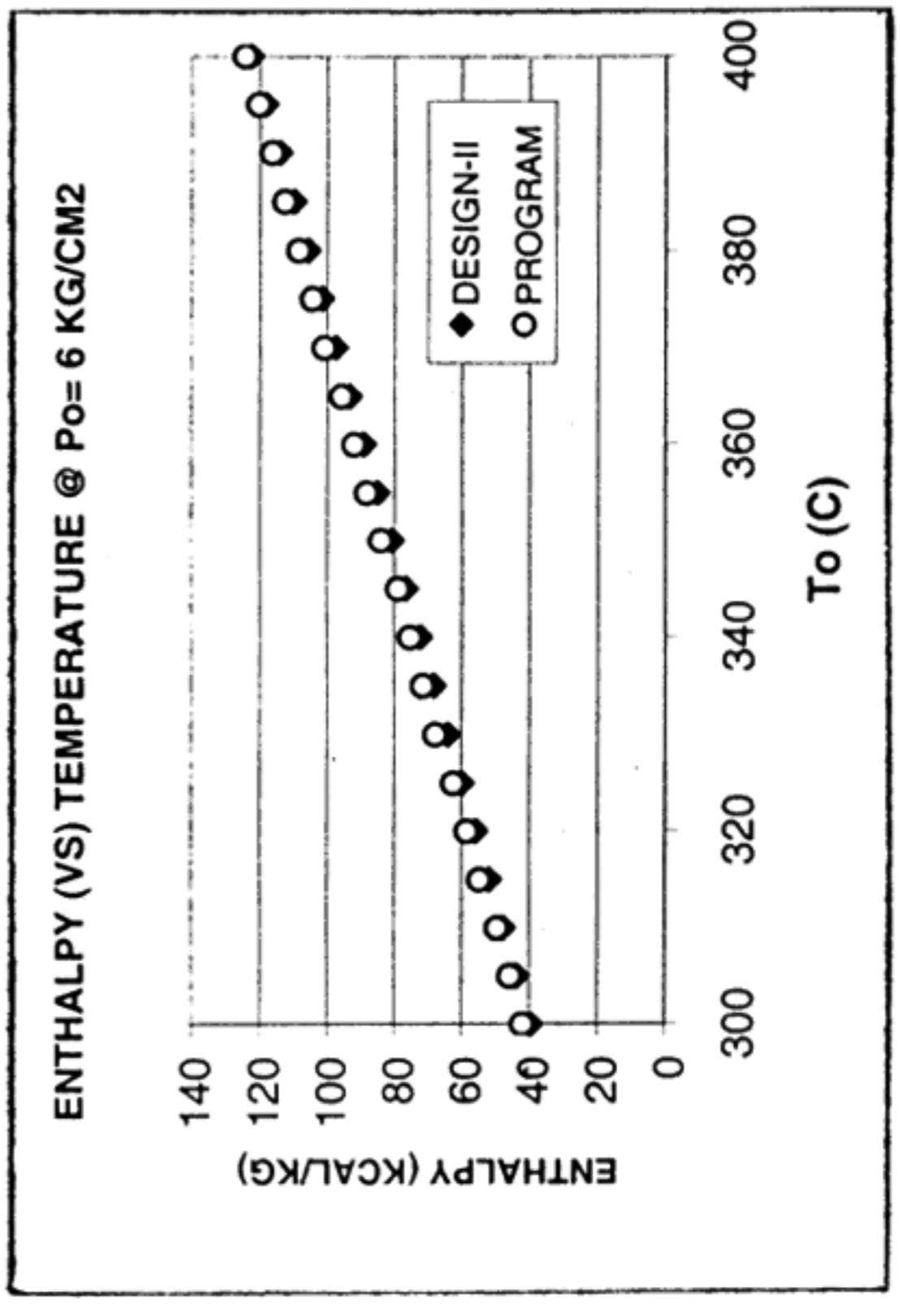
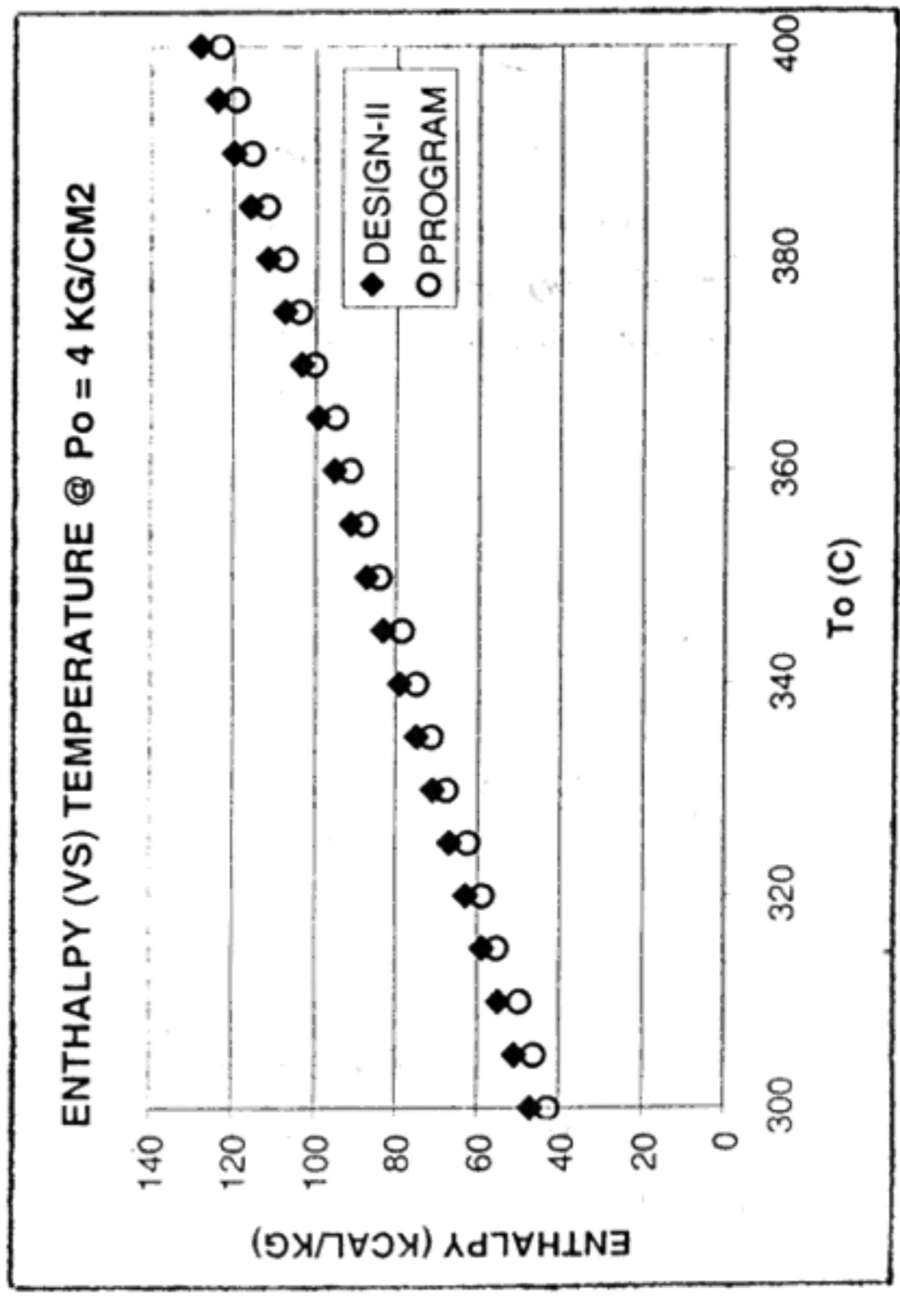
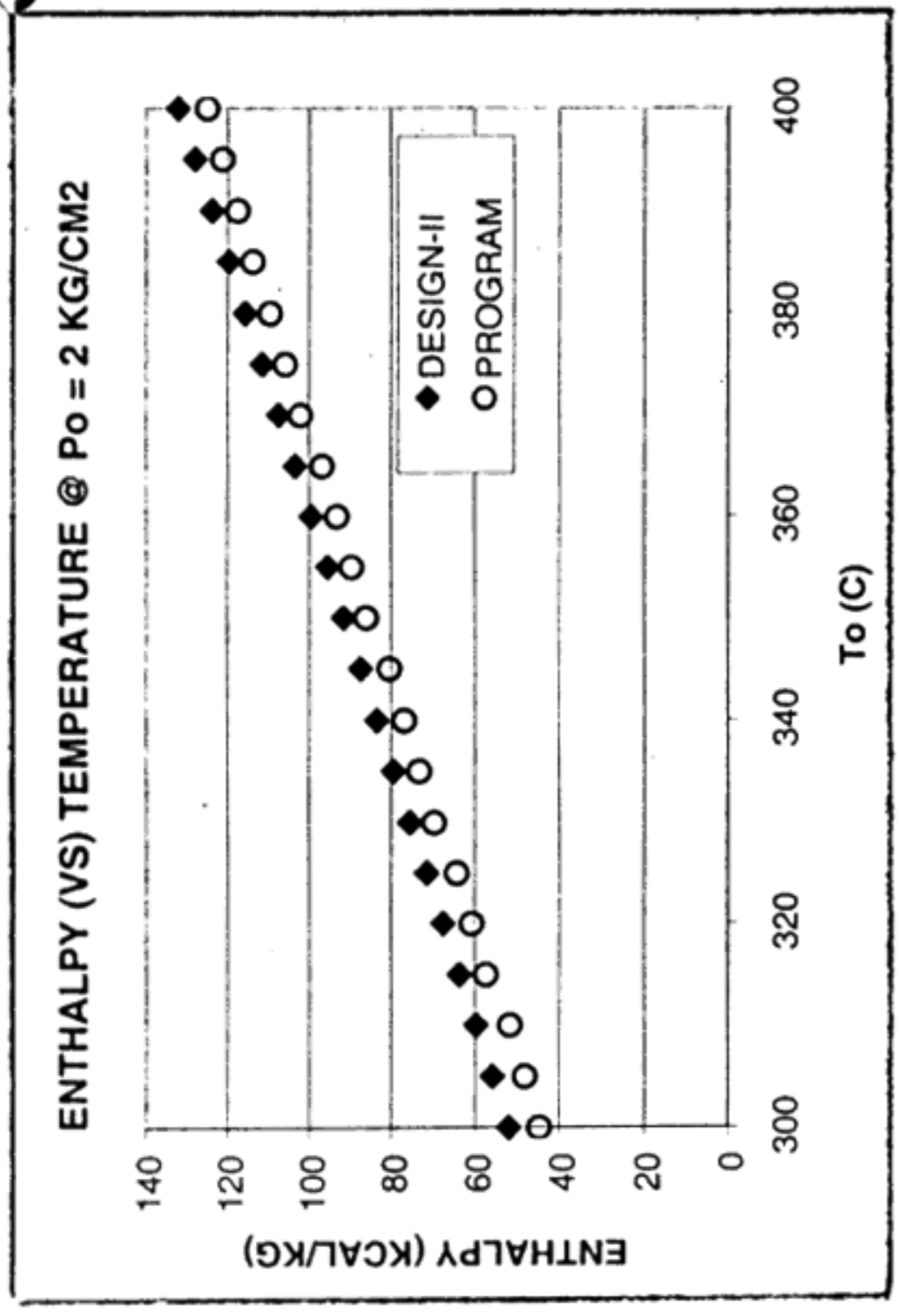
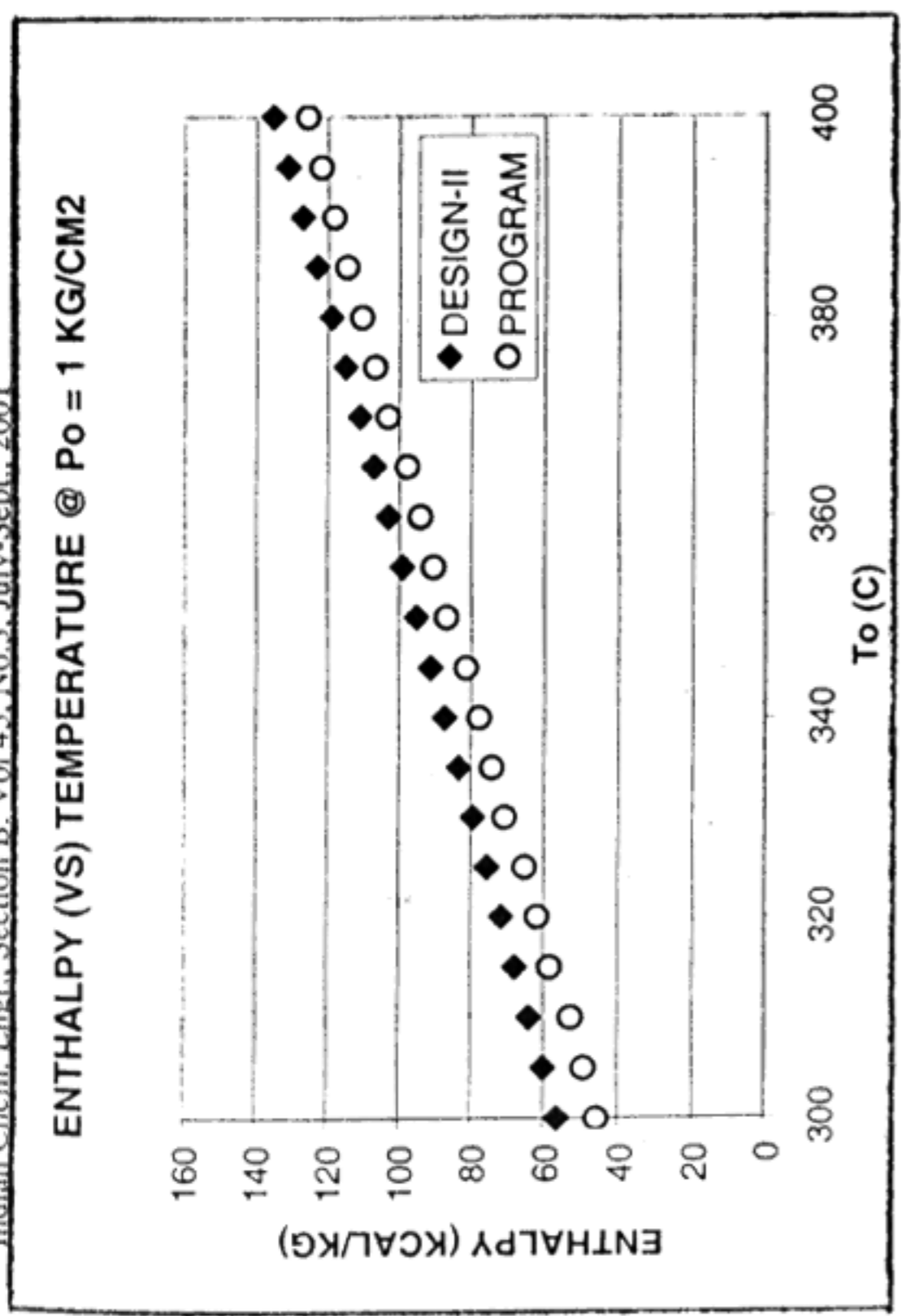


Fig. 1 Comparison of Enthalpy Calculated by Design-Ii and Program.