ChE class and home problems

The object of this column is to enhance our readers' collection of interesting and novel problems in chemical engineering. Problems of the type that can be used to motivate the student by presenting a particular principle in class, or in a new light, or that can be assigned as a novel home problem, are requested as well as those that are more traditional in nature, which elucidate difficult concepts. Please submit them to Professor H. Scott Fogler, ChE Department, University of Michigan, Ann Arbor, MI 48109.

A PRACTICAL APPLICATION OF MASS BALANCES

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A COURSE IN MASS (and energy) balances is essentially a course in solving a large number and variety of problems. This has been our approach to teaching mass balances, and many of the problems we assign can be described by *given this and this, calculate that.* This seems reasonable in light of the fact that one of the primary reasons for doing mass balances is to determine unknown flowrates and compositions from a limited amount of data.

Another application of the mass balance technique is in checking the consistency of measured data from a process. It is, therefore, also useful to assign problems which demonstrate this concept. The problem presented here is one such example.

PROBLEM

(a) A process steam boiler (operating at steady state) at a coal conversion plant fires coal gas from a continuous vertical retort. The fuel analysis is given in Table 1. An environmental test crew has made measurements of the flue gas emissions in the stack; the measured dry flue gas analysis is given in Table 2. Over the duration of the testing, the molal humidity of the combustion air supply was 0.05 mole moisture per mole dry air. Using the law of conservation of mass, check the consistency of the data.

(b) The boiler described in part (a) operates at a thermal input of 25 MW, and the higher heating value of the fuel gas has been determined as 17.97 MJ/m^3 at 15°C and atmospheric pressure. In addition to determining the dry flue gas analysis, the environmental test crew has made several other measurements. The temperature of the flue gas was found to be 325°C. A particulates traverse revealed negligible stack solids, a flue gas moisture content of 38% by volume, and a stack gas velocity of 5.75 m/s. The chimney diameter is known to be 2.06 m, and the burners were thought to be operated with about 17% excess air over the duration of the testing. Using the law of conservation of mass, check the consistency of the data.

TABLE 1
Fuel Analysis

Component	Volume %
CH_4	22.0
CO	18.0
H_2	49.4
O_2	0.4
CO_2	4.0
N_2	6.2

TABLE 2
Dry Flue Gas Analysis

Component	Volume %
CO_2	10.0
CO	0.8
O_2	4.0
N_2	85.2

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SOLUTION

(a) The flow diagram is shown in Figure 1, with the system defined as the boiler plant. The basis for subsequent calculations is 100 mol of fuel gas fed to the boiler (actually the time required to fire this quantity of fuel gas).

The solution strategy follows that outlined for this type of problem by Lewis *et al.* [1]. Their procedure first calls for the assumption that there is a balance between input and output of all major elements in the process except one. The data consistency check is then achieved by seeing if an equality exists between input and output of the last element.

To systemize the choice of elements and balances, the following scheme is recommended in ref. [1] for this sort of process:

1. **carbon balance to relate fuel to dry flue gas**
2. **nitrogen balance to relate dry flue gas to air supply**
3. **oxygen balance to determine moisture in flue gas**
4. **hydrogen balance to check data consistency**

The parameters for these balances are shown in Table 3. The amounts of dry flue gas (X), dry air (Y) and flue gas moisture (Z) calculated from Table 3 via

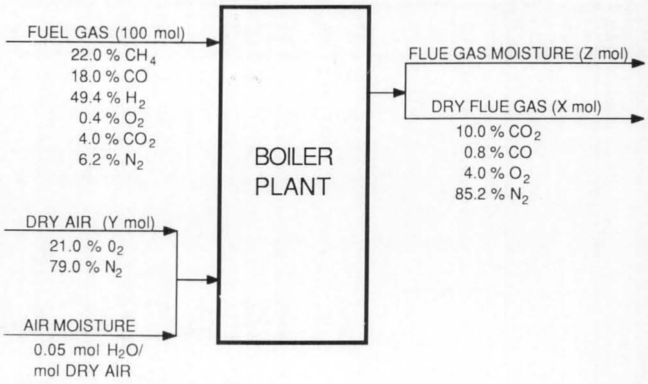

FIGURE 1. Flow diagram for process steam boiler plant.

the carbon, nitrogen and oxygen balances are 407.4 mol, 431.5 mol, and 112.3 mol, respectively. The hydrogen balance yields an input of 115.0 mol H_2 and an output of 112.3 mol H_2 (less than 3% difference). Considering that all measurement errors have been lumped in the hydrogen balance [1], the input and output of hydrogen show good agreement. The data from this part of the problem are considered to be consistent.

(b) The data which are to be checked for consistency in this part are the percent excess air, flue gas moisture content, and stack gas velocity. Table 4 shows the calculations for the theoretical oxygen (77.3 mol),

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TABLE 3
Mass Balance Parameters on a Basis of 100 mol Fuel Gas (equating volume % and mole%)

STREAM	CARBON (mol)	NITROGEN (mol)	OXYGEN (mol)	HYDROGEN (mol)
Fuel gas	22.0 (as CH_4) 18.0 (as CO) 4.0 (as CO_2)	6.2 (as N_2)	0.4 (as O_2) 9.0 (as CO) 4.0 (as CO_2)	49.4 (as H_2) 44.0 (as CH_4)
Dry air	-------	0.79 Y (as N_2)	0.21 Y (as O_2)	--------
Air moisture	-------	--------	0.05 Y/2 (as H_2O)	0.05 Y (as H_2O)
Dry flue gas	0.008X (as CO) 0.1X (as CO_2)	0.852X(as N_2)	0.04 X (as O_2) 0.008 X/2 (as CO) 0.1 X (as CO_2)	---------
Flue gas moisture	------	---------	0.5 Z (as H_2O)	Z (as H_2O)

X = mol dry flue gas
Y = mol dry air
Z = mol flue gas moisture

TABLE 4
Theoretical Oxygen Calculations on a Basis of 100 mol Fuel Gas

COMPONENT	AMOUNT (mol)	COMPLETE COMBUSTION EQUATION	THEORETICAL O_2 (mol)
CH_4	22.0	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	44.0
CO	18.0	$CO + 1/2\, O_2 \rightarrow CO_2$	9.0
H_2	49.4	$H_2 + 1/2\, O_2 \rightarrow H_20$	24.7
O_2	0.4	–	- 0.4
			77.3

which corresponds to a theoretical air value of 368.1 mol. From part (a), the actual dry air supplied is 431.5 mol. The calculated value of 17.2% excess air agrees with the estimate given in the problem statement.

The amounts previously determined for the dry flue gas (407.4 mol) and flue gas moisture (112.3 mol) indicate a moisture content of approximately 22% in the flue gas. Clearly this does not agree with the measured value of 38%; one explanation is that the measurement is incorrect [2]. As shown in the following analysis, however, there is a more likely explanation.

The fuel firing rate is calculated as 58.8 mol/s by dividing the boiler thermal input by the higher heating value of the fuel gas, correcting to STP, and assuming ideal gas behavior. Since the basis previously used was 100 mol of fuel gas, the scale factor for the process is 0.588 mols/s/mol.

Using 407.4 mol dry flue gas from part (a) and a flue gas moisture content of 38%, the amount of moisture in the flue gas is determined to be 249.7 mol. This gives a value of 657.1 mol for the total amount of flue gas, which, when multiplied by the scale factor, becomes a molar flowrate of 386.4 mol/s. Correcting from STP to 325°C and assuming ideal gas behavior, the volumetric flowrate of the flue gas is 19.0 m^3/s. Dividing this by the cross-sectional area of the chimney, a stack gas velocity of 5.70 m/s is obtained. This compares favourably with the given value of 5.75 m/s.

It is unlikely that the measurements of both flue gas moisture content and stack gas velocity are wrong. The data, therefore, indicate that more water is leaving the system than is entering. A plausible explanation is the existence of a leak in a water tube inside the boiler.

CONCLUSION

Although the solution has been presented here in a straightforward manner, the open-ended nature of the problem can create difficulties for some students. In particular, part (b) requires analysis and judgement skills in addition to the knowledge of how to perform a mass balance. For this reason we have found it best to offer exposure to problems of this type in class tutorials and home assignments before using them on tests and exams. This approach generally results in a favourable student response, in addition to illustrating the power and usefulness of the mass balance technique.

REFERENCES

1. Lewis, W. K., A. H. Radasch, and H. C. Lewis, *Industrial Stoichiometry: Chemical Calculations of Manufacturing Processes,* second edition, McGraw-Hill, New York; pp 114-118 (1954)
2. Felder, R. M., and R. W. Rousseau, *Elementary Principles of Chemical Processes,* second edition, John Wiley & Sons, New York; pg 85 (1986) ❐

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and have a number of interesting projects that have been on the back burner for the lack of such students.

DEPARTMENTAL ADMINISTRATION

Because of the size of the department and the number of degrees it awards (we also administer the freshman chemistry program required of all engineering undergraduates), the chairman is assisted by five associate chairmen. Barbara Kebbekus acts as administrative officer for the chemistry division, and Reginald Tomkins is responsible for recruiting and advising all of our undergraduate students and handles industrial liason. Richard Trattner administers the enviromental science program. Arthur Greenberg advises graduate students in the applied chemistry program, and Basil Baltzis is responsible for recruiting and advising chemical engineering graduate students.

Departmental staff includes two adminstrative assistants, two secretaries, a machine shop supervisor, a laboratory supervisor, and two lab assistants.

REFERENCES

1. National Action Council for Minorities in Engineering, *NACME News,* p 6 (August, 1988)
2. "Frontiers in Chemical Engineering Education: Research Needs and Opportunites," National Research Council, National Academy Press, Washington, DC (1988) ❐