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ARTIFICIAL INTELLIGENCE IN PROCESS CONTROL: KNOWLEDGE BASE FOR THE SHUTTLE ECS MODEL

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ABSTRACT

The general operation of KATE, an artificial intelligence controller, is outlined. A shuttle ECS demonstration system for KATE is explained. The knowledge base model for this system is derived. An experimental test procedure is given to verify parameters in the model.

SUMMARY

A scaled down version of the shuttle ECS system is being built to test KATE, an artificial intelligence expert system at KSC. KATE requires an accurate mathematical model of the ECS, called the knowledge base. This report gives the model derivation.

An explanation of how KATE works is given. Each component must be described and loaded into KATE as a LISP "frame". The description includes a functional equation and component relationships to aid fault diagnosis.

The ECS system consists of four ducts branching from a manifold which is supplied with chilled air. Each duct has a heater, flow meter, a butterfly control valve, and two manual (butterfly) valves. The air temperature and flow rate is to be controlled precisely by KATE. Component failure is to be initiated to test KATE's diagnostics.

The mathematical description relates flow rates to pressures. A major element is the determination of component loss coefficients. The heater loss coefficient and time constant were derived from the fundamentals of flow over fins. Butterfly valves show little control at angles less than 40° and too much control at angles greater than 60°. Manual valve settings in each duct are obtained which will optimize the valve control sensitivity.

An experimental procedure is given to verify the loss coefficients of key components. Loss coefficients are expressed in terms of pressure and flow rate readings.

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SYMBOLS AND SUBSCRIPTS

Symbols

a	admittance
A	duct area
C	constant
D	duct diameter
f	pipe friction factor, 0.017
g_c	32.17 lbm-ft/lbf - sec^2
$\dot{H}$	heat transfer rate
K	loss coefficient
L	duct length
$\dot{M}$	mass flow rate
P	pressure
T	temperature, Rankine
V	velocity
α	venturi loss, fraction of ΔP
B	D_2/D_1
ρ	air density
θ	butterfly valve setting or heater divergent wall angle to horizontal

Subscripts

a	aft
b	bend
c	cabin
d	dump
e	entrance
f	forward or fins
h	manual (hand) valve
L	line (duct)
m	motorized (control) valve
p	payload
r	reheat (heater)
s	supply
T	total
1	venturi entrance
2	venturi throat

I. INTRODUCTION

KATE (Knowledge-based Autonomous Test Engineer) is a knowledge-based expert system being developed at Kennedy Space Center. The basic concept of an expert system consists of two parts. The first part is a knowledge base which describes the process hardware. This allows for a simulation of real time behavior, and it can be used to gather information about the status of the system. The second part is the software or artificial intelligence (AI). AI represents a good design engineer, systems engineer, and operator in a single software package that operates on the knowledge base representation of the system. Software capabilities include graphical display generation, simulation, process control, redundancy management, constraint checking and diagnostics. In particular, unanticipated failures can be diagnosed, and instructions can be given to get the system to a new desired state, or correct it and return it to a normal state.

KATE has been under development at Kennedy Space Center since 1985. The first full test of the system will be carried out this Fall. The process chosen for the task is a scaled down version of the shuttle environmental control (ECS) ground system. Such a system consists of thermal, fluid and electrical components. In addition, the sensors and control actuators are both analog and digital. A mathematical description of these elements constitutes the process knowledge base. The summer task is to assist Kennedy engineers obtain this knowledge base.

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II. HOW THE SOFTWARE WORKS

Artificial intelligence (AI) systems are composed of three parts: (1) input/output, (2) knowledge base, and (3) operating system. Input consists of the sensors (transducers), supplying the system with pressure, temperature, flow, etc. data in the form of voltages to an analog-to-digital converter. Outputs are the commands to actuators regulating the variables of temperature, flow, etc. The knowledge base is a mathematical description of the process. The operating system is the set of algorithms which interprets the data and knowledge base, controls the process and diagnoses faults. The latter is KATE. Her language is LISP although other AI languages include ADA and C.

2.1 KNOWLEDGE BASE

The operating system is sufficiently general that it can be applied to all processes. It is the knowledge base that changes with each process. There are two types: expert rules and model base.

With expert rules, the programmer sits down with the plant operator and grills him on how he controls the process. A plant is usually modified over the years, and the operator may be the only person who knows the system. He is aware of the system idiosyncrasies and often learns by experience why a certain procedure works. The programmer must root out these rules of intuitive behavior. These rules are of the form: if   , then   . For example, if valve one is open or valve two is closed and liquid level switch two is set, then open valve three. The rules are adaptable to Boolean algebra. Some large systems have been known to take five man-years and generate thousands of rules. Drawbacks to this approach are several.

a. It cannot react to unknown conditions.

b. There is no diagnosis when faults occur. The process must be shut down with a simple sensor failure.

c. The intelligence and system operation resides mainly within the knowledge base rules; and therefore, they change with each process.

KATE uses a "model base" knowledge base. It depends on a mathematical description of each component in the process. Thus, each measured variable can be calculated also. A comparison of the two is the basis for a complete fault diagnosis. At the same time the AI system can suggest alternative commands to circumvent the failed component. Intelligence resides in the operating system, and only the component mathematical descriptions need to be loaded when a new process is brought under AI control.

As an example of a component description, consider a venturi flow meter in an air duct. Normally, one calculates the volume flow rate from the differential pressure reading. In our case we want the mass flow rate which will include the duct temperature and pressure (in place of density) calculation. The equation may look like

$$DP = 6.2P\dot{M}^2/T$$

Notice that the equation is the inverse of the normal output $\dot{M}$, i.e. we want the differential pressure in terms of the flow rate. The reason is that the AI system must calculate DP to compare it with the measured DP for fault diagnosis.

All components and variables are prepared for programming by placing its information into a "frame". An example follows for the differential pressure above.

LISP FRAME

```
(deframe DPA
    (nomenclature aft duct differential pressure)
    (a i o PRESSURE)
    (source-path P
                 T
                 F)
    (in-path-of DPA TRANSDUCER)
    (status (/(*(6.2)(square Ṁ)(P))T)))
```

Line 1. Variable symbol.

Line 2. Description.

Line 3. An instance of. What is the category? A variable: pressure, temperature, flow? An item that can fail: transducer, relay, heater?

Line 4. Source-path. What variables are used to calculate DPA?

Line 5. In-path-of. What component is in the path of DPA?

Line 6. Status. The equation for DPA.

2.2 KATE'S OPERATING SYSTEM

KATE'S operating system consists of algorithms for fault diagnosis which function basically by forming lists. After a delay for command dynamics to settle out, the following procedure is used to identify failed components and determine alternate commands to circumvent the problem.

a. Get new measurements from sensors throughout the process. Compare these new measurements with previous readings stored in memory. Form a list of any measurements that change by more than a prescribed amount.

b. Go to the knowledge base and calculate the variable that is measured for each discrepancy in the above list. If the calculated and measured values disagree, place the deviants into a second list for the DIAGNOSER.

c. When a component fails, it is likely to generate many deviants for the second list above. The DIAGNOSER goes to the knowledge base and forms a list of all possible components that can be related to the deviant. Recall the frame for differential pressure. Line 5 identifies a transducer as a possibility. Line 4 has several variables that can be related to components upstream through other frames. The computer knows which categories (Line 3) in every frame that can fail. Every deviant measurement caused by the failed component will have a similar, though not identical, list of process components that factor into its reading. Every list will have several process components in common. KATE uses elementary set theory to identify those components with the most intersections and ranks them in the order of most likely to cause the deviations. Starting with the first component in the list, KATE simulates the component failure modes and calculates every measurement in the process from the knowledge base. The component mode can be ON/OFF for a relay to multiple command voltages for a motor control valve. KATE proceeds through the list until a component and its failure mode is found which will cause agreement between all process measured and calculated variables. If KATE is told to find a new command to circumvent the failure and to maintain variable settings, the procedure is the same as above. Command changes are simulated until the desired result is obtained. This is valuable at Kennedy Space Center where systems often have built in component redundancy.

III. SHUTTLE ECS DEMONSTRATION UNIT

A top view drawing of the scaled down shuttle environmental control system (ECS) is shown in Figure 1. It is built within a 18 by 13 foot open block-house. An external chiller (a mobile air force purge unit) supplies 100 lbm/min of cold air at 43° F, 3 to 4 psig through an 8 inch line. The line turns 180° into a 12 inch manifold which distributes the cold air to four ducts for the simulated shuttle payload, aft, forward and cabin areas. A motorized dump valve balances the out flow for the total of 100 lbm/min.

Each duct is identical and has the same components with one exception: the payload duct is a nominal 6 inch pipe (6.065ID) while the remaining ducts are a nominal 3 inch pipe (3.068ID). The components are as follows.

a. Keystone hand operated butterfly valve.

b. Chromalox air heater (6kw and 15kw, payload duct).

c. Leeds and Northrup venturi meter.

d. Keystone motorized butterfly valve.

e. Keystone hand operated butterfly valve.

Each duct also contains, as indicated in Figure 1, the following.

a. Two remote pressure sensors.

b. One remote temperature sensor.

c. Two pressure gauges.

d. One temperature gauge.

e. One remote differential pressure sensor (venturi).

Both the air temperature and flow rate are controlled in each of the four ducts. The temperature is controlled to within + 0.5° F over the range: 60 to 70° F. The flow rate is controlled to within 0.2 lbm/min where the range for each duct is as follows.

Payload duct:	28 to 55 lbm/min
Cabin duct:	4.6 to 12 lbm/min
Forward duct:	6 to 17.6 lbm/min
Aft duct:	11.4 to 14.2 lbm/min

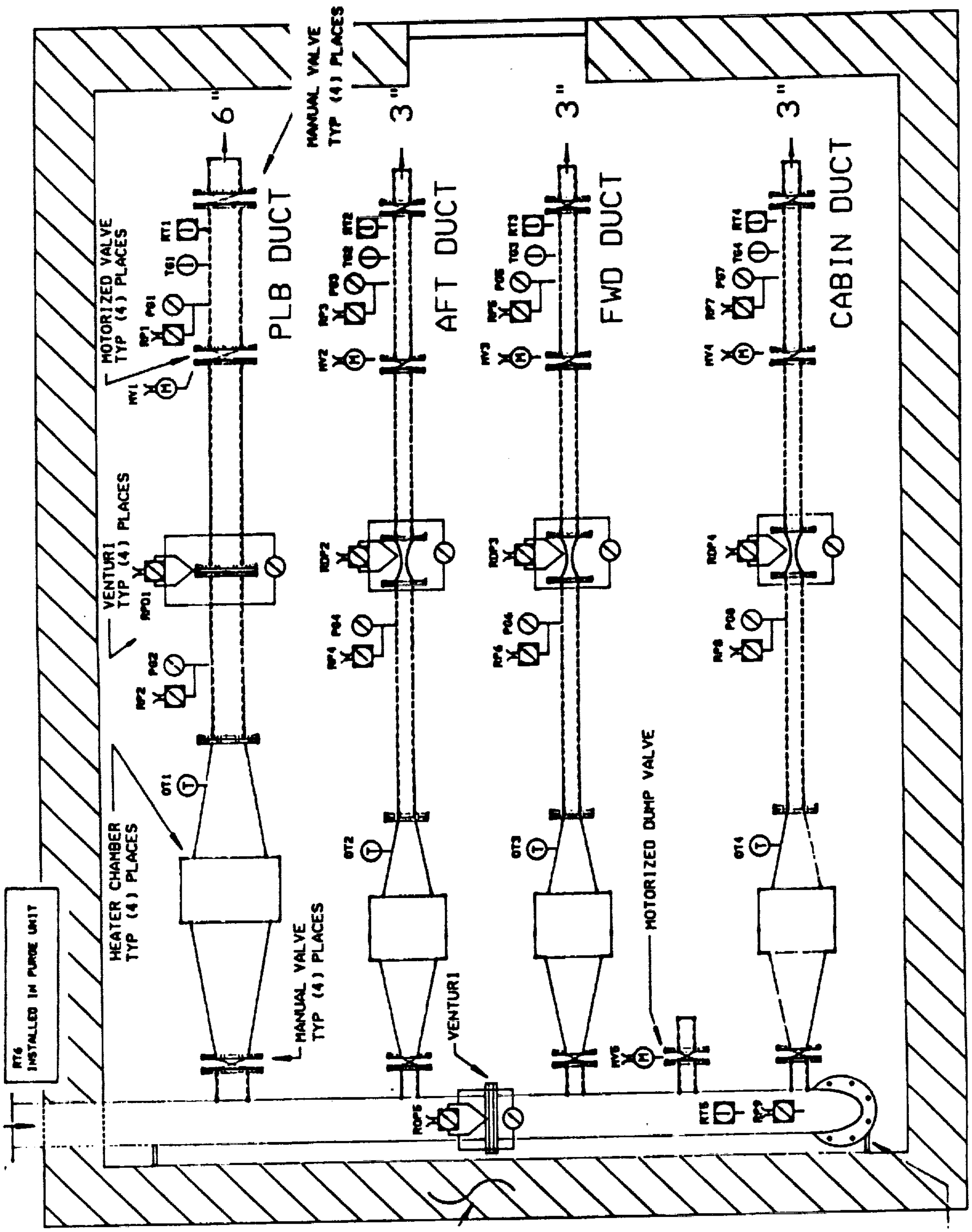

Figure 3-1. Shuttle ECS Test Unit

IV. ANALYTICAL DESCRIPTION

4.1 BASIC EQUATIONS

A mathematical description of the overall test unit consists of equations relating the flow rate and pressure drops for each duct in terms of admittance.

$$P_s = f(\dot{M}_s)$$

$$\dot{M}_s = \alpha_s\sqrt{P_s - P_m}$$

$$\dot{M}_p = \alpha_p\sqrt{P_m}$$

$$\dot{M}_a = \alpha_a\sqrt{P_m}$$

$$\dot{M}_f = \alpha_f\sqrt{P_m}$$

$$\dot{M}_c = \alpha_c\sqrt{P_m}$$

$$\dot{M}_d = \alpha_d\sqrt{P_m}$$

$$\dot{M}_s = \alpha_t\sqrt{P_m}$$

$$\alpha_t = \alpha_p + \alpha_a + \alpha_f + \alpha_c + \alpha_d$$

$$P_m/P_s = \alpha_s^2/(\alpha_t^2 + \alpha_s^2)$$

Each duct includes a number of components and elements in series. The duct admittance can be found in terms of the individual admittances. For example, the aft duct admittance is found from

$$\alpha_a = \left[1/\sum_{n=1}^{N} 1/\alpha_{an}^2\right]^{1/2}$$

where n is an individual admittance.

The admittances for each element can be expressed in terms of a loss coefficient K. The pressure drop is given by

$$\Delta P = K\rho V^2/2g_c$$

where $M = \rho A V$. Rearranging,

$$\alpha = A\sqrt{2\rho g_c / K}$$

For a perfect gas,

$$\rho/\rho_o = \frac{P}{P_o}\frac{T_o}{T} \quad \text{(use absolute values)}$$

Then

$$\alpha = \sqrt{2\rho_o g_c}\, A \sqrt{P T_o / P_o T} / \sqrt{K}$$

For air at 70° F, 14.7 psia,

$$\alpha = 11.0 A \sqrt{P T_o / P_o T} / \sqrt{K} \quad \text{lbm/min} \quad \sqrt{\text{psi}}$$

$$\alpha = 2.09 A \sqrt{P T_o / P_o T} / \sqrt{K} \quad \text{lbm/min} \quad \sqrt{\text{in.} H_2O}$$

and for elements in series

$$\alpha = 11.0 A \sqrt{P T_o / P_o T}\, [\textstyle\sum K_n]^{-1/2}$$

We will now review the individual components and elements in order, starting with the purge unit. The aft duct branch will be taken but the calculated variables are the same for each duct unless stated otherwise.

4.1.1 SUPPLY PIPE.

$$K_{SL} = fL/D = (0.017)(20)/(.666) = 0.5$$

4.1.2 SUPPLY FLOW METER.

$$\dot{M}_s = Y C_d A_2 \sqrt{\frac{2\rho g_c \Delta P_T}{(1 - B^4)}} \quad (\Delta P_T \text{ across taps})$$

$$Y \text{ (compressibility factor)} \approx 0.98 \text{ (neglect)}$$

$$\Delta P_v \text{ (loss across venturi)} = \alpha \Delta P_T$$

$$\alpha = 0.10 \text{ for } \theta = 7^o,\ B = 0.45$$

Flow Measurement Engineering Handbook REF TC 177

$$C_d = 0.96$$

$$K_{SV} = \left(\frac{1 - B^4}{B^4}\right)\left(\frac{\alpha}{C_d^2}\right) = 2.5$$

Loss between P_s and RP9,

$$\sum K = K_{SL} + K_{SV} = 3.0$$

4.1.3 90° BEND.

$$K_{SB} = 0.3$$

4.1.4 EXPANSION TO MANIFOLD.

$$K_{se} = \left[1 - \left(\frac{d}{D}\right)^2\right]^2 = .3$$

4.1.5 CONTRACTION: MANIFOLD TO DUCT.

$$K_{me} = 0.45$$

$$= 0.36 \quad \text{(PLB)}$$

4.1.6 BUTTERFLY VALVE (MANUAL 1).

$$K_{ah1} = \left(\frac{1.56}{1 - \sin\theta} - 1\right)^2 \qquad \theta > 25°$$

See Section 3.1.12

4.1.7 REHEAT CHAMBER.

Gradual enlargement

$$K_1 = \left[1 - \left(\frac{d}{D}\right)^2\right]^2 = .9$$

Fin drag

$$F_f = \frac{\rho V_*^2}{2g_c} A_f \times \frac{1.328}{\sqrt{\mathfrak{R}_{eL}}} \times 400 \quad \text{fins}$$

Cylinder drag

$$F_c = c_d \frac{\rho V_\infty^2}{2g_c} A_c \times 6 \text{ cyl.}$$

Loss coefficient due to drag

$$\Delta P A_R = (F_f + F_c)$$

also

$$\Delta P = K_2 \rho V_\infty^2 / 2g$$

$$K_2 = A_f \frac{1.328}{\sqrt{\Re_{eL}}} 400 + c_d A_c \times 6$$

$$= 76$$

correct to duct velocity at A

$$K_2 = 76(A_r / A)^2 = .25$$

total reheat chamber loss

$K_{ar} = 0.9 + 0.25 = 1.2$ (not calculated for PLB but scales up similarly)

reheat chamber time response

$\dot{H}_1 = MCdT_f/dt$ heat transfer to fin capacitance

$\dot{H}_2 = (T_f - T_o)h_f A_f$ heat transfer to film resistance

$$\dot{H} = \dot{H}_1 + \dot{H}_2 = MCdT_f / dt + h_f A_f (T_f - T_o)$$

But heat transfer to the film resistance is given to the air.

$$(T_f - T_o)h_f A_f = \dot{M}_a C_p (T_o - T_i)$$

Eliminating T_f and rearranging $\dot{H}$,

$$MC\#(1 + (\dot{M}_a C_p / h_f A_f)) d(T_o - T_i) / dt + \dot{M}_a C_p (T_o - T_i) = \dot{H}$$

The time delay t_d is four time constants or

$$t_d = \frac{4MC}{\dot{M}_a C_p}(1 + (\dot{M}_a C_p / h_f A_f)) = 3.25 \text{ min}$$

$$= 4.0 \text{ (50\% fin efficiency)}$$

where

$$h_f = 0.664 \frac{k}{L} P_R^{1/3} (R_{eL})^{1/2} = 4 \times 10^{-3}$$

$$A_f = 840 \text{ in}^2 \text{ (est.)}$$

$$C = 0.11 \text{ Btu/lbm°F}$$

$$M = 11.5 \text{ lbm (est.)}$$

$$C_p = 0.24$$

reheat chamber sensitivity

$$\text{Power} = \dot{M}_a C_p (T_o - T_i)$$

at full power the temperature change of the air is

$$T_o - T_i = \frac{6000W \times 3.414 \frac{\text{Btu/hr}}{W} \times \frac{1 \text{ hr}}{60 \text{ min}}}{12 \text{ lbm/min} \times 0.24 \text{ Btu/lbm°F}} = 118°$$

For an 8 bit D/A converter, the temperature can be controlled to within 0.5° F at flow rate mid-range. Worse case: low cabin flow rate (4.6 lbm/min) where $T_o - T_i = 308°$ or control to within 1.2° F.

4.1.8 DUCT SECTION HEATER TO RP4 SENSOR.

$$K_{aL1} = fL/D = 0.18$$

$$= 0.09 \text{ (PLB)}$$

Loss between RP9 and RP4,

$$\sum K = K_{SB} + K_{se} + K_{me} + K_{ah1} + K_{ar} + K_{aL1}$$

$$= 2.4 + K_{ah1}$$

4.1.9 DUCT SECTION SENSOR TO FLOW METER.

$$K_{at2} = fL/d = 0.1$$

$$= 0.05 \text{ (PLB)}$$

4.1.10 FLOW METER.

Same equations as the supply flow meter.

$$3 \text{ in. duct : } B = 0.671, \ \theta = 5°$$

$$6 \text{ in. duct : } B = 0.45, \ \theta = 7°$$

Meters for ducts 4 inches in diameter or less have a slight sudden contraction from duct size A to area A_1, at the high pressure tap.

$$K_1 = \frac{(1 - B^4)}{B^4}\left(\frac{\alpha}{C^2}\right)\left(\frac{A}{A_1}\right)^2 = 1.6$$

$$K_2 = .28 \text{ (sudden contraction)}$$

$$K_{av} = K_1 + K_2 = 1.9$$

$$K_{ai} = \frac{(1 - B^4)}{B^4}\left(\frac{\alpha}{C^2}\right) = 2.5 \text{ (PLB)}$$

4.1.11 DUCT SECTION TO MOTORIZED BUTTERFLY VALVE.

$$K_{at3} = fL/D = 0.1$$

$$= 0.05 \text{ (PLB)}$$

4.1.12 MOTORIZED BUTTERFLY VALVE

If both hand butterfly valves are full open, a simple calculation will show that the motorized valve must be set to nearly closed $\theta \approx 70°$ for the mid-flow range where its $K \approx 600$. A one degree change will change K by 150, much too sensitive for satisfactory flow rate control. Furthermore, at nearly open $\theta = 20°$, a one degree change will change K by 0.5. If the hand valves take too much of the loss to achieve the mid-flow rate setting, the motorized valve loses control. A logical solution is to select a minimum permissible setting for the maximum flow rate. This will maintain control, yet allow a maximum sensitivity for control. Selecting $\theta_{min} = 40°$

$$(K_{am})_{min} = 11$$

Now we can determine the total K by summing the Ks along a streamline from P_s (purge unit) to a selected duct end at $P = 0$ psig. The Ks in the larger supply duct should be corrected to the common velocity of a distributing duct or

$$K_{new} = K_{old} \times \left(\frac{\dot{M}_s / A_s}{\dot{M}_a / A_a} \right)^2 = 1.4 K_{old}$$

Then

$$\dot{M}_a = a \sqrt{P_s}$$

where $a = 11.8A[\sum K_n]^{-1/2}$ using an average value for the pressure/temperature correction. The butterfly setting for the two hand valves is found from the maximum duct flow with the control valve at $\theta = 40°$:

$$(\dot{M})_{max} = 11.8A[20 + 2K_h]^{-1/2} \sqrt{P_s}$$

solving for each duct ($P_s = 3.5$ psig)

$K_{ah1} = K_{ah2} = 50$ $\quad \theta = 53.8°$

$K_{fh1} = K_{fh2} = 29$ $\quad \theta = 49.1°$

$K_{ch1} = K_{ch2} = 75$ $\quad \theta = 57°$

$K_{ph1} = K_{ph2} = 54$ $\quad \theta = 54.4°$

Butterfly control valve settings for the average flow rate in each duct (hand valve settings above) are

$K_{am} = 40$ $\quad \theta = 51.9°$

$K_{fm} = 108$ $\quad \theta = 59.7°$

$K_{cm} = 194$ $\quad \theta = 63.6°$

$K_{pm} = 109$ $\quad \theta = 59.7°$

4.1.13 DUCT SECTION CONTROL VALVE TO SENSOR RP3.

$$K_{al3} = fL/D = 0.10$$

4.1.14 DUCT SECTION SENSOR RP3 TO HAND VALVE.

$$K_{al4} = fL/D = 0.10$$

4.1.15 BUTTERFLY VALVE (MANUAL 2).

$$K_{ah2} = \left(\frac{1.56}{1 - \sin\theta} - 1\right)^2 \qquad \theta > 25°$$

See Section 3.1.12

V. EXPERIMENTAL DESCRIPTION

An accurate model of the process begins with an analysis of the components and a calculation of the most probable values for the variables. Along the way certain engineering parameters must be estimated. The final link in the model development is an experimental program to verify the analysis and its associated parameters. For the ECS system there are several verifications that are most important.

(1) Characteristic curve of the purge unit: $P_s = f(\dot{M}_s)$

(2) Loss coefficient versus angle for the butterfly valves.

(3) Flow meter loss coefficient.

(4) Heater loss coefficient.

(5) Heater response time.

The ECS system is now being assembled and it should be completed for tests by the middle of August. The initial tests to verify the parameters will be run without KATE, using the various gauges that accompany the remote sensor units. I propose the following test procedure while recording all gauges.

5.1 OPEN ALL DUCT BUTTERFLY VALVES

a. Record minimum P_s on the characteristic curve along with its $\dot{M}_s$.

b. Find the open manual butter fly loss coefficient K_{ah2}. It should be the same for all valves.

$$\dot{M}_a = \alpha\sqrt{PG3}$$

$$\alpha = c[K_{al4} + K_{ah2}(\text{open})]^{-1/2}$$

c. Find the venturi loss coefficient K_{av}

$$\dot{M}_a = \alpha\sqrt{PG4 - PG3}$$

$$\alpha = c[K_{al2} + K_{av} + K_{al3} + K_{am}(\text{open}) + K_{al3}]^{-1/2}$$

d. Find the heater loss coefficient K_{ar}

$$\dot{m}_a = a\sqrt{PG9 - PG4}$$

$$a = c[(K_{SB} + K_{s})1.4 + K_{ah1}(\text{open}) + K_{ar} + K_{aL1}]^{-1/2}$$

e. Check the supply admittance.

$$\dot{M}_s = a\sqrt{P_s - PG9}$$

$$a = c'[K_{SL1} + K_{sv} + K_{sL2}]^{-1/2}$$

f. Check all ducts for identical gauge readings.

5.2 VARY CONTROL VALVE SETTINGS IN CABIN DUCT.

a. Obtain $K_{cm} = f(0)$

b. At K_{cm} (closed) check to see if manifold pressure given by PG8 agrees with P_s. This verifies that the supply line loss is negligible. Record P_s, $\dot{M}_s$ for another point on the characteristic curve.

5.3 CLOSE REMAINING DUCTS IN TURN

a. Completely close aft, forward and payload bay ducts, recording P_s and $\dot{M}_s$ after each closing.

b. Slowly close the dump valve. Continue recording P_s, $\dot{M}_s$ for the characteristic curve. Stop when P_s reaches a maximum.

5.4 DETERMINE HEATER TIME RESPONSE

Introduce a step change in the heater command. Measure the outlet air temperature every 10 seconds until a new temperature stabilizes.

VI. CONCLUDING REMARKS

KATE depends on an accurate knowledge base flow model. The ECS system is relatively simple with various loss coefficients the predominant determinate. Among the loss coefficients calculations for bends, contractions, expansions, smooth pipe lengths and even venturi flow meters are straight forward from handbooks. These values are small and very reliable. By subtracting these contributions between pressure gauges, the less certain loss coefficients for the heater and butterfly valves can be verified experimentally. The heater loss coefficient was calculated from aerodynamic drag principles. The formula for the butterfly valve loss coefficient versus angle was found in the "Handbook of Hydraulic Resistance", translated from Russian. There is no indication of the formula source, likely to be theoretical.

The single critical element in the knowledge base is the butterfly valve. The valve angle is set by activating the butterfly drive motor for a specified time. The multiple spur/worm gear drive is likely to suffer backlash. Thus, open loop positioning cannot be reliable. KATE should use the position potentiometer with some type of software feedback. The problem is compounded by the butterfly flow sensitivity. The mid-range flow rate valve settings for the three series (two manual plus one control) butterfly valves are approximately 55°. These settings were established to give the smallest allowable change in loss coefficient per angle of movement, thus the widest range for the angle over the flow range. Yet, the valve is so nonlinear that the high flow rates will change by 0.15 lbm/min per degree while the low flow rates will change by 0.55 lbm/min per degree over the angle span of 30° (forward duct example).

Finally, the heater time response was calculated to be approximately 4 minutes independent of the temperature command change magnitude. The length of time appears to be large. Thus, it represents an element of anticipation in the experimental study.