Development of an in-car climatic control system

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This paper describes in detail the original methods used in the design and development of a microprocessor-based climate control system for the XJ40 Jaguar car. It takes the concept of air conditioning and applies modern technology and materials to produce a unit for a new passenger car. It describes those areas of design where experience in automotive air conditioning has shown the need for improvement, and also explains the operational procedures. The theories presented can be used in any automotive application and lead through concept and development to a final design implementation.

1 INTRODUCTION

A new vehicle in today's competitive environment must meet the most stringent performance standards on reliability and performance. This is easily measured for speed and weight and the other, oft-quoted parameters, but it must also compete in areas where regular measurements fail to grasp the overall effects. The climatic environment, the living space, the comfort in which a driver is maintained enhances not only safety but also the perceived performance of the total vehicle. Any changes in the interior climate may drastically affect the vehicle user to an extent where the user is physically uncomfortable.

To achieve Jaguar objectives on the XJ40 meant a complete redesign of the in-car climate control system to incorporate new technology, improved performance and increased reliability.

2 CUSTOMER REQUIREMENTS

Before embarking on a blind redesign of a climate control system, it was necessary to establish the users' requirements. What the customer expected from a system was quite obviously of paramount importance.

To this end a series of programmes were started involving ergonomics, competitor surveys, customer surveys and, of course, a close examination of the physiological requirements of the human body.

Many factors were assessed for both understanding and necessity—whether outlets should be warm or cool, what level of airflow was acceptable—and every feature had to be considered for all world markets. This meant wide-ranging ambient conditions from sub-zero arctic conditions to extreme desert situations, from night to high radiant sunlight and from torrential rain to arid drought. Each change in environment must be crossed with no change to the vehicle user and to do this in a controlled manner was the prime consideration. From the investigations into customer requirements a set of ideal conditions were formulated; these were to be achieved by the climate control system which could alter the three main variables:

Temperature
Airflow
Humidity

The surveys also specified low noise as an additional requirement: therefore the task was to meet the needs of temperature and airflow as quietly as possible. Failure in any one specific area could mean dissatisfaction for the user.

3 OBJECTIVES

From the customers came a clear requirement for performance and reliability which complemented the company targets for the new vehicle to form the major objectives:

(a) improved performance over current cars and potential competitors,
(b) increased reliability over potential competitors.

Added to these were a series of company objectives:

(a) reduced weight over current cars,
(b) maintain or reduce existing package size.

These were the main objectives from which the new design would germinate.

4 SPECIFICATION

Having defined the objectives it was necessary to describe the final unit in engineering terms—the specification. This was the far-reaching document which covered all areas of the unit's performance, quality, reliability, weight and noise which would be capable of meeting the company's objectives and hence the customer's requirements.

Every attempt was made in the preparation of this document to prevent the avoidable error and to stop self-interpretation of the company's aims.

This unit was one of the first major systems to carry a full design and process failure mode effects analysis procedure. It took many months to prepare and traced any potential problem and worried it to a satisfactory solution.

A number of suppliers were then issued with this document from which feasibility studies were prepared; a final selection of supplier was then made.

5 THE UNIT

The final design can, in simple terms, be described as a flap-controlled air distribution system. Figure 1 is a cross-section schematic of the main unit, from which it

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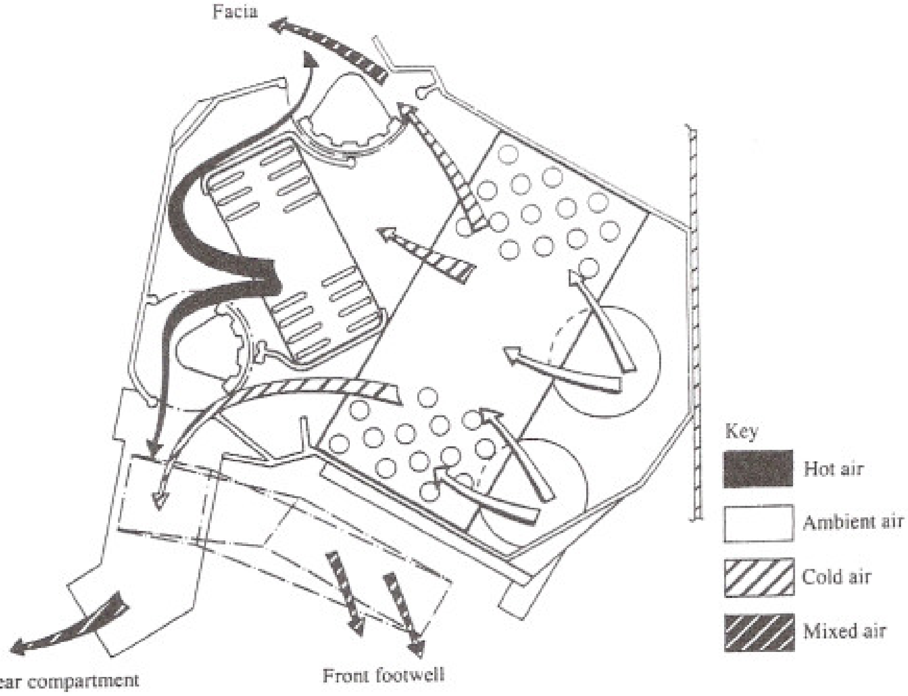


Fig. 1 Schematic of unit

can be seen that air is diverted by two rotary air valves through the heater matrix. This air is proportional to the position of each flap and its relationship to the other.

The main components are held in a three-part plastic case with access for all electrical and mechanical services (Fig. 2). Air is initially routed through an evaporator where it is cooled and dried and is then either warmed or passed directly to the distribution system for dispersion in the car.

Air pressure is generated from two separate blowers, one on either side of the unit, again housed in plastic cases with independent flap and speed control.

The total package is controlled via an electric switch pack mounted in the centre console. From this panel, which is the only visible part of the unit, the user may select any of the variables.

The control brain which interprets the required signals from the unit and user is the microprocessor. This is housed on the side of the main unit and is an 8 bit device developed from a one-chip microcomputer, the 3870. Its shape has been governed by installation constraints and is not of any significance. Specific demands on the microprocessor are made by the user via the control panel, by the unit via positional sensors and by the climatic conditions via a number of measurement sensors. The processor will analyse the various input signals and make a decision for change, if required, which is output to the unit. At this point the rotary air valves would alter position, thereby changing the in-car condition. A complete system is therefore a closed loop with various measurement devices correcting unit output to maintain the user setting.

6 COMPONENTS, THEIR FUNCTION AND DESIGN

The case for the complete unit is designed in three parts, a rear half to house the evaporator and two front sections holding the heater matrix and rotary air valves. The case (Fig. 3) is a talc-filled polypropylene injection moulding, the material being chosen for its good thermal properties, light weight and strength. The split of the case was designed to avoid possible leak paths for the evaporative condensate and to enable assembly of the moving parts.

Inside the main case are the two rotary air valves

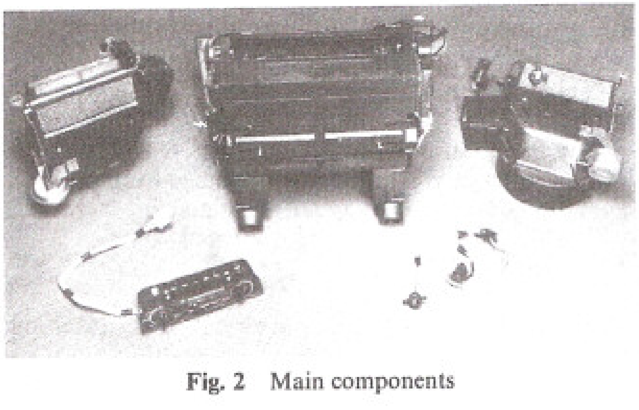


Fig. 2 Main components

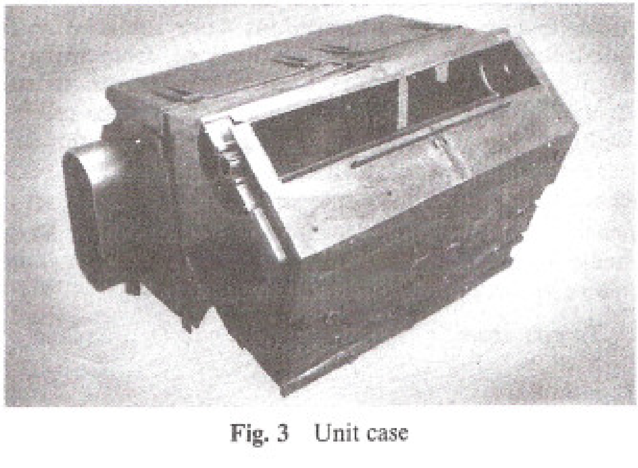


Fig. 3 Unit case

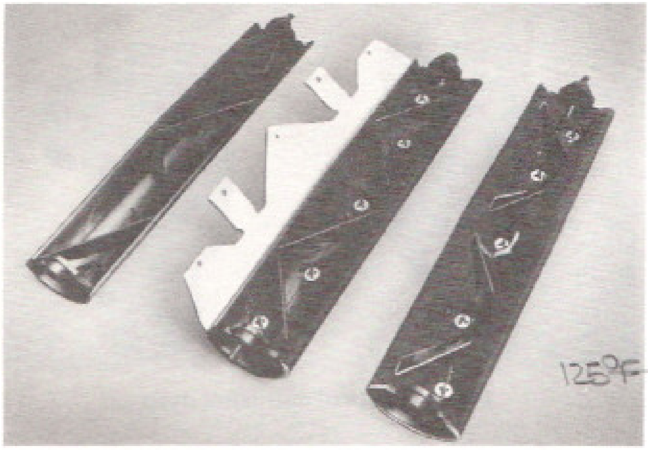


Fig. 4 Rotary air valve

(Fig. 4). These are glass-filled nylon to ensure torsional rigidity as the driving force would be at one end of the central shaft. The sealing edges for these flaps are achieved with a nylon material which wipes across rigid sections of the main case mouldings.

The two main components of the system are also housed within the case assembly: these are the heater matrix (Fig. 5) and an evaporator. The heater matrix is a copper–brass radiator with microfoil fins of very close spacing for performance. The performance was derived using the Series III saloon as a base. Body conductance was measured at various speeds and a straight line prediction made for the working speeds of the vehicle in −30°C ambients.

The graph in Fig. 6 shows vehicle speed against body conductance in watts per kelvin and shows speed limits for Canada and northern Europe where −30°C ambients can be expected. Also shown is the measured miscellaneous heat pick-up from engine and exhaust systems and an overlay of the heater matrix output in kilowatts.

From this is can be found that with an ambient of −30°C and a temperature demand of 24°C the unit must generate 3.58 kW to overcome general heat loss. Additional heat must be generated to increase interior temperature. The specification requires 95 W/K which at 55 miles/h generates 9.88 kW, thereby giving 6.3 kW interior heat. This target was achieved as proven in climatic chamber tests where air outlet temperatures are 46°C average, equating well with calculated data (see Fig. 6).

The matrix is a split unit with removable inlet and outlet pipes. This, coupled with detachable side plates to the actual unit case, means it is easily serviced in the car without removing the main system. Located on the inlet pipe to the matrix is an electrical temperature switch used for isolation of the systems blowers until a satisfactory water temperature is available. This prevents cold air being drawn into the car during warm-up conditions.

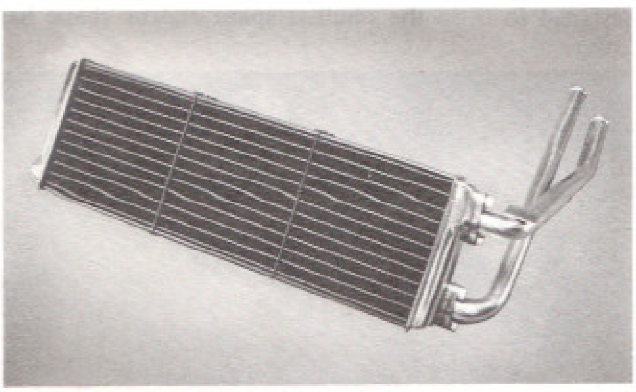
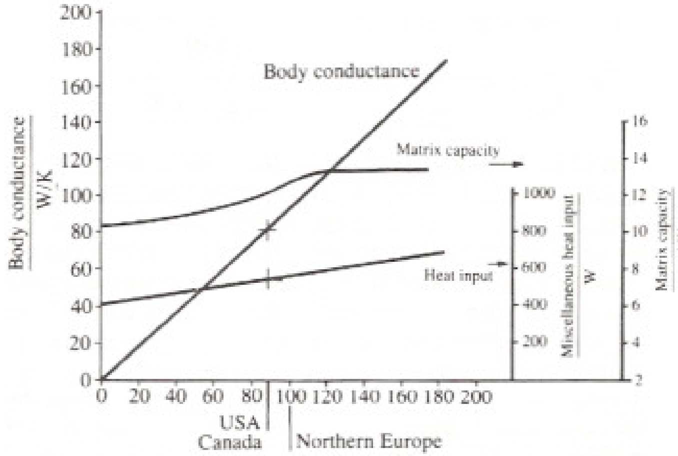


Fig. 5 Heater matrix

The evaporator (Fig. 7) is a copper tube aluminium fin unit. The fins possess a crinkle appearance to aid water dispersion, thereby maintaining thermal performance during operation. The required evaporative performance was calculated using a maximum world ambient of 52°C with 900 W/m² solar load. To maintain an average interior temperature of 24°C the evaporator must input 4.5 kW to overcome body conductance, driver plus one passenger, miscellaneous heat and solar load.

With the unit under full load it requires an outlet temperature of approximately 4°C to maintain an interior average of 24°C; this equates to 7.39 kW. Using both input criteria means that a total of 11.89 kW is required to maintain the initial objective.

The target specification was, however, set at 8 kW, because full cooling capacity is generated on recirculat-



Assumptions

Set speed	55 mile/h
Miscellaneous heat input	0.5 kW
Heat loss, body conductance	4.32 kW
Heat input from driver and one passenger	0.24 kW
Ambient temperature	−30°C
Average interior temperture	24°C
Total heat loss to maintain 24°C interior at 55 mile/h in a −30°C ambient	3.58 kW
Capacity of heater matrix in a −30°C ambient with a 74°C coolant temperature	9.88 kW
Total capacity left to heat interior	6.3 kW

Target performance

1.25 kW per person installed

95 W/K at 88°C, water flow 0.15 L/s, air flow 100 L/s

$$\theta = \frac{H}{mc}$$

$$= \frac{9.88}{0.13} \text{ at 74°C, air 100 L/s, water 0.15 L/s}$$

= 76°C temperature difference in a 30°C ambient

= 46°C air out as proven in climatic testing

Fig. 6 Vehicle speed versus body conductance ed air and not fresh. This fact reduces the air on temperature from 52°C steady state to 24°C and hence reduces the required power to 8.14 kW.

Ambient 52°C in-car average 24°C, $\Delta T = 28$°C

Body conductance or heat gain at 55 miles/h	2.24 kW
Driver + 1 passenger heat gain	0.24 kW
Miscellaneous heat gain at 55 miles/h	0.5 kW
Sun load at 900 W/m^2 (approx.)	1.5 kW
Total heat input	4.5 kW

Air density at 52°C = 1.1 kg/m^3
Air density at 24°C = 1.3 kg/m^3
Vehicle airflow at full cold = 140 L/s

Air outlet temperature to maintain 24°C average interior = 4°C; therefore $\Delta T = 48$°C:

Therefore evaporator performance to reduce air temperature by 48°C = 48 × 1.1 × 140 = 739 W
= 7.39 kW

Total evaporator performance = 7.39 + 4.5
= 11.89 kW

However, on full recirculated air $\Delta T = 20$°C. Therefore,

evaporator performance = 20 × 1.3 × 140
= 3.64 kW
Total evaporator performance = 3.64 + 4.5
27,774 Btu/hr = 8.14 kW 2.3 tons

Within the evaporator is another type of temperature sensor; the type used here is an electronic semiconductor coupled with a small circuit to enable accurate linear measurement of temperature. This unit is placed inside the evaporator to measure the fin temperatures and its function is twofold. Firstly, it must control the air conditioning compressor by cycling its clutch as evaporative demand is met and, secondly, it must prevent the evaporator icing, which can be caused by the condensed water freezing within the fins of the evaporator. This must not occur as it prevents airflow and would eventually affect interior temperature and freon circuit performance.

Many peripherals are attached to the main case moulding. The air distribution to the feet is achieved using two plastic mouldings which slide into the front case sections (Fig. 8). These are easily detachable for access to the unit and for alternative designs if necessary. They are also made from a talc-filled polypropylene.

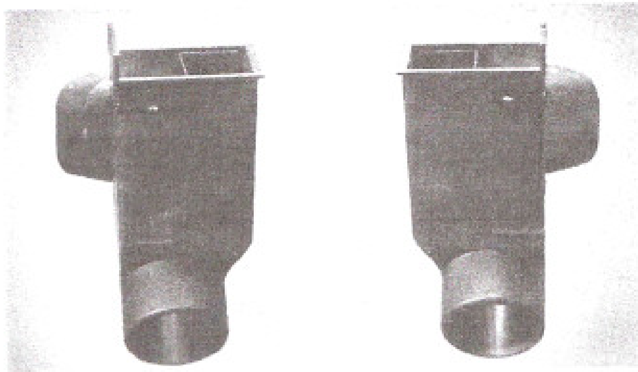


Fig. 8 Footwell distributor ducts

Attached to the end of the rotary air valves are the drive motors. Two motors are used, one for each flap. They are small d.c. motors connected to each shaft via a worm gear and three spur gears, which are moulded in plastic to reduce both noise and weight and have a reduction ratio of 1500 : 1. This provides the torque strength to overcome seal friction at the extreme temperatures found inside the unit.

At the opposite end of the rotary air valves are the positional sensors. These are rotary potentiometers which form the return leg of a closed-loop system (Fig. 9). It is necessary for the drive motors to know at what position they must stop and this is provided by these potentiometers. The location was chosen to overcome any torsional twist occurring in the flap itself. The sensors are held on separate steel plates which are calibrated prior to unit fit, and this negates the need for awkward setting procedures at both production and service stages.

Suspended below the unit are four vacuum solenoids which control air vents and the water valve (Fig. 10). These are positioned on two removable plates for serviceability. The connecting harnesses carry vacuum restrictors which act as dynamic dampers on the moving vents. These prevent sudden changes in setting from the inherently fast operation of vacuum solenoids.

One other major component is attached to the case of the unit: the microprocessor itself (Fig. 11). The micro is a dedicated computer designed specifically for the air conditioning system. In production form it carries a masked 8 bit microcomputer within a support circuit of amplifiers, analogue to digital converters, resistors, capacitors, diodes and voltage regulators. The circuit is designed to fit in the smallest space and its shape has

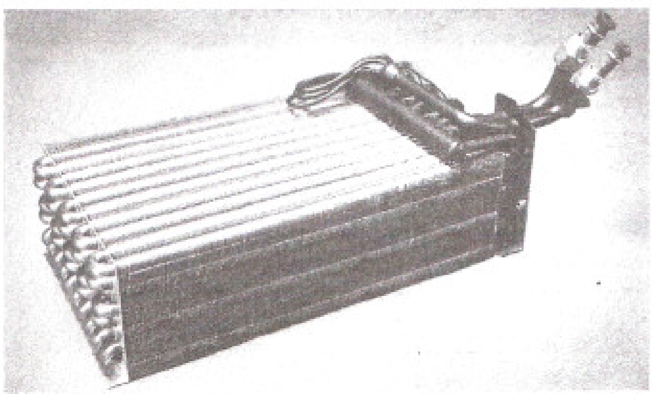


Fig. 7 Evaporator

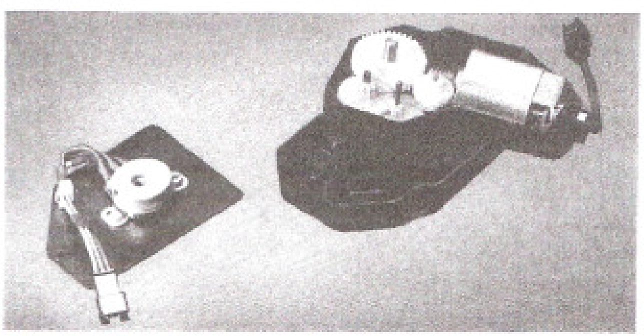


Fig. 9 Rotary flap drive motor and feedback potentiometer

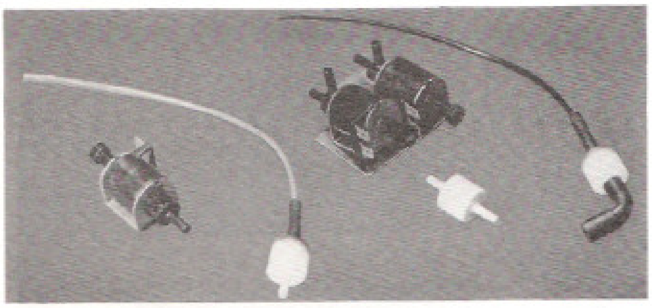


Fig. 10 Vacuum solenoids

been tailored to fit the contour of the main unit. The printed circuit board has used multi-layer techniques to assist with radiofrequency protection while the circuit design has been paramount in providing an intrinsically safe electrical unit for use in an automotive environment. The vehicle uses a number of microprocessors and it is necessary to protect each unit from interference and interfering with other units. The circuit, once built on to the board, is then conformally coated to protect against the environment. This also makes each unit tamperproof. It will in normal circumstances prevent unauthorized testing due to its all-enveloping nature. In the design of the system, this was considered and a 45 pin diagnostic access plug was built into the unit. This is compatible with the vehicle test equipment developed for the dealers and enables a full diagnosis test to be completed. Each processor is fully tested and functionally operated before it reaches the vehicle to ensure the high level of reliability required.

Surrounding and supporting the main unit are a number of items which combine to make a complete climate control system. The major parts are the air blowers (Fig. 12). There are two blower units mounted on either side of the main case. Each consists of a three-part plastic moulding in the same talc-filled polypropylene as the main case. The high-performance motor has been isolated from the casing to ensure low noise and carries a high level of balance at its production stage. The squirrel cage rotors have been designed for high air pressure with a low noise and these have been made in a sniamid material for low weight and good rigidity. Integral with the blower casing is a flap and actuation mechanism to alter the air intake mode from fresh interior air to recirculated air. This change is made upon demand of the microprocessor and is a vacuum function signalled from one of the previously mentioned vacuum solenoids. Within each blower is a heatsink assembly containing the electronic speed control devices which form the power side of the infinitely variable fan speed. The running signal is provided by the microprocessor, which is then actioned by the individual blower circuitry. To reduce voltage drop within the vehicle harness a relay is positioned within the blowers to allow direct power feed upon demand; this is effected during maximum performance requirements or defrost selections.

In the right-hand blower unit is another electronic semiconductor and circuit to measure temperature. This device is identical in performance to the unit mounted in the evaporator but in this instance it measures the ambient air temperature. The microprocessor uses this information to compensate for changes in exterior conditions which would affect the vehicle interior.

The control system can measure exterior ambients but it must also measure interior ambients. This is achieved using a third sensor of the same design, giving a linear voltage output for temperature change. The in-car sensor is mounted in the crash roll and has air forced across it by an aspiration system supplied from the right-hand blower outlet. The aspirator is a single plastic injection moulding.

To complete the sensing system (Fig. 13) a fourth sensor has been included. This unit is mounted in the top of the facia at the vehicle centre-line. Its function is to measure radiant sun load and enable the microprocessor to compensate for the direct heat load associated with high levels of sunlight. It uses a photo transistor and circuit housed in a button-sized plastic mount.

Control of the total system is via a switch pack mounted in the centre console (Fig. 14). This is the only part of the climate control system available to the user.

With a combination of rotary, slider and push button controls all variables and user options can be selected. The design of controls, their meanings and layout is a difficult and somewhat subjective field. Legislation too requires certain symbols to be included and various lighting conditions achieved. Consideration is therefore twofold: regulations must be met and the user must be catered for. The final design (Fig. 15) was based on an ergonomic survey and concept style for the options available from the unit. The need to retain the individuality of a Jaguar meant keeping a rotary control for

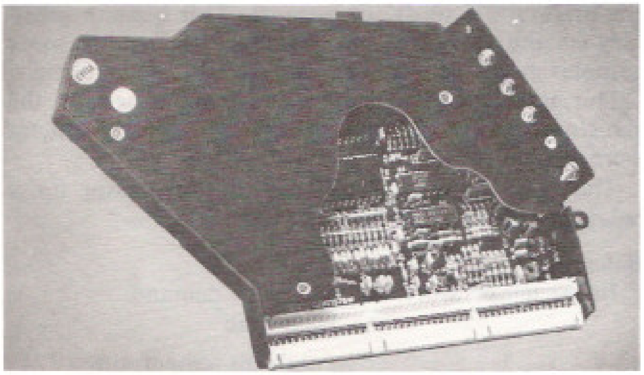


Fig. 11 Microprocessor

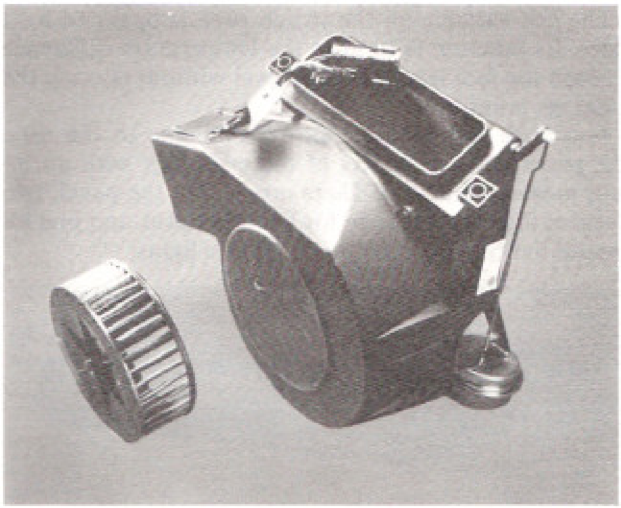


Fig. 12 Air blower

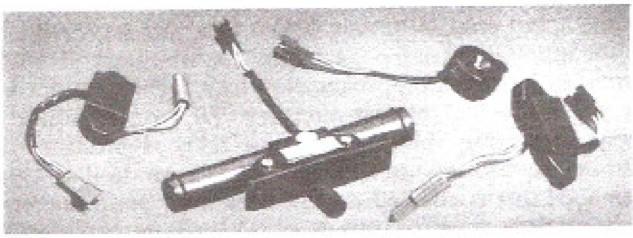


Fig. 13 Control system sensors

fan speeds and temperature select with the modern facilities added, via slider and push buttons.

To overcome transient changes in vehicle use a manual automatic override has been included which if operated gives the option of maintaining full heat output, full cold output or any set point in between, regardless of ambient conditions. Another area where optional change occurs is for air distribution. It is occasionally felt more air is required to the screen and this can now be achieved by selection of another push button. An economy device has been included which disconnects the air conditioning compressor on demand. This option would be used in cold climates as it turns the unit into a heater only. A second pair of buttons has been added to control the evaporator temperature. With these and the economy function the user may select a total of four variables for evaporator temperature. These are jointly called humidity control. The options have allowed control of the evaporator temperature at four different levels. The lowest control point is 0–0.25°C and would be used for maximum capacity cooling and high ambient conditions. This will remove the maximum amount of moisture from the air. The second control point is 3.9–4.15°C. The temperature control in-car is maintained but less moisture is removed from the air. This setting is ideal for medium ambient conditions. The third selection controls at 7.1–7.35°C and would be used in low ambient conditions. The fourth, and final, option is economy. The evaporator would reach ambient temperatures as described earlier.

Use of these functions will allow selected variation in the level of humidity in the car and may be altered for personal preference or ambient conditions. The set point of the evaporator will affect power consumption for the compressor: hence fuel economy may be gained without loss of air conditioning using these controls.

The last variable on the switch pack is operated by a slider. Its function is to alter the temperature difference between the face level and foot level without altering the in-car set point.

These are the option controls available to the user. The panel will retain any of these settings with an in-built memory function. There are, within the panel, two levels of illumination, one for control status and one for general lighting operated with the side lights.

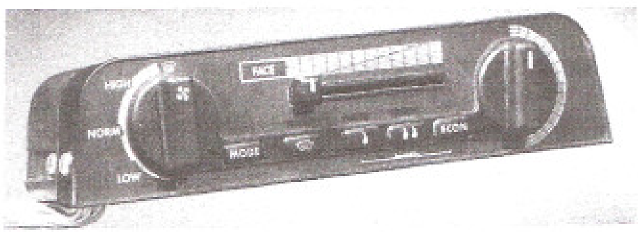


Fig. 14 Control panel

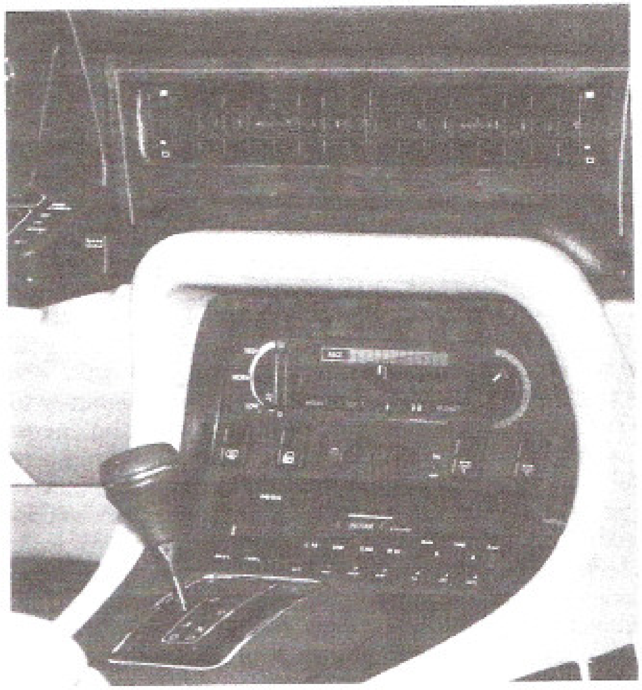


Fig. 15 The final design on the centre console

The panel now meets legislation requirements and offers the user all variables available from the system.

7 DEVELOPMENT PROCESS

Development of the unit began on a rig. Here a series of prototype plastic components were assembled and run to prove the basic principles of a two-flap system. At the initial stages a simple analogue control was used.

The first processor chosen was a 3870 micro with a 2K EPROM facility. The software was developed around the basic unit design and specification taking into account the proposed feature level, sensors and controls. The software routine is shown in Fig. 16. Use of the processor enabled changes to be made quite simply as the software was written around a series of look-up tables. An emulator was produced to match the 3870 through which all our original development was run.

A series of environmental tests was conducted in some of the most severe conditions available. This involved the Arizona desert and the Canadian arctic. Temperatures varied from −38°C to a high of +49°C, so enabling complete testing to all forseeable extremes.

Many of the variables were changed during these tests and the processor was increased in capacity from the original 2K to 4K of memory. This became necessary as the software was developed, becoming more complex as problems were encountered and overcome.

During tests the sensors were modified around the vehicle and their effects modified until control criteria were met.

The calculation undertaken by the processor for a balance condition and hence no change is:

Balance

$$\text{In-car temperature} = \text{temperature demand} - \text{solar load} - \left(\frac{\text{ambient temperature} - 24}{10}\right)$$

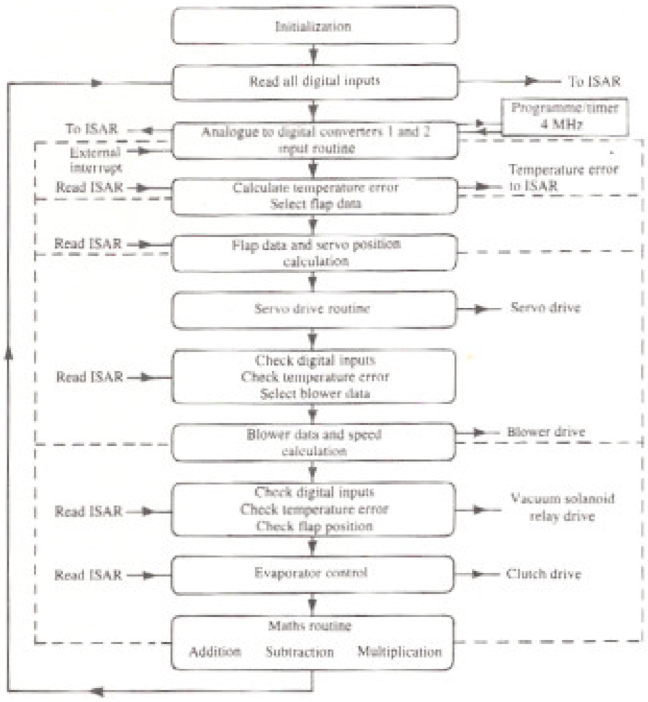


Fig. 16 The software routine

If an imbalance is found a temperature error is recorded and an output made to the servo drives and blower controls. For this condition the calculation becomes:

Imbalance

$$\text{Temperature error} = \text{temperature demand} - \left[\text{in-car temperature} + \text{solar} + \left(\frac{\text{ambient temperature} - 24}{10}\right)\right]$$

Temperature demand and in-car temperature are the overriding factors throughout this calculation. The ambient sensor is a one-tenth divider for each degree beyond an average 24°C and the solar sensor has a maximum effect of 2°C below set point. The values for solar compensation were developed from the photoelectric response of the phototransistor during daily cycles in the United States, Canada and the United Kingdom. The final specification is shown in Fig. 17.

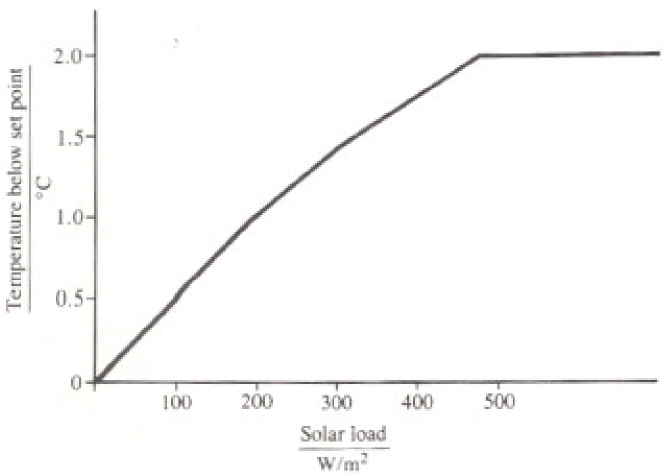


Fig. 17 Variation of temperature below set point with solar load

Once an alteration had been made it was necessary to retest a batch of units to assess the effect on a production basis. As the unit became more refined in terms of tooled components so the effect of processor changes became more predictable.

The accuracy of the microprocessor and its ability to repeat conditions exactly brought with it some problems. The hardware and manufacturing tolerances of the system could not match that of the processor. This meant averaging results from groups of units to obtain the optimum processor settings to account for possible production variations. Monitoring of this condition is a requirement of the specification and will be an ideal control medium for production.

8 THE FINAL PRODUCT

To enable the unit to comply with original requirements meant a great deal of control throughout the production and development stages. To ensure correct build a series of jigs and fixtures are used and on-line diagnostic equipment, itself microprocessor controlled, developed.

The unit carried both a design and build failure mode effect analysis, which is continually being updated. Line trials were completed by both the manufacturer and Jaguar to assess all aspects of unit build and installation before full volume was reached.

Final in-house control on the system is achieved by rig test. It is a further requirement of this specification that units throughout the life of the vehicle undergo full performance checks.

It is also part of the the company system to monitor user/customer feedback for future modifications or features that become necessary.

The company's aim from concept to production has been to build a reliable and efficient unit to complement and enhance the total vehicle.

This has been achieved.

9 ACHIEVEMENTS

Performance—heat output increased by 6.2 per cent
cold output increased by 19.4 per cent
airflow increased by 33 per cent with stepless control

Reliability—FMEA processes completed
rig endurance testing 20 000 cycles on units complete
car endurance testing complete
off tool component faults reduced

Weight—unit weight reduced by 7.2 per cent

Size—present package size maintained

Cost—reduction in cost by 30 per cent

ACKNOWLEDGEMENT

The author would like to thank the following for their assistance in the preparation of this paper and their work on the system: Delanair Limited, in particular Mr R. J. Thorburn; Gaydon Technology for their excellent facilities; and colleagues at Jaguar Cars Limited.