1965

Effect of air temperature on energy utilization of growing-finishing swine

Duane Wilbur Mangold

Iowa State University

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UTILIZATION OF GROWING–FINISHING SWINE.

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EFFECT OF AIR TEMPERATURE ON ENERGY UTILIZATION
OF GROWING-FINISHING SWINE

by

Duane Wilbur Mangold

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Head of Major Department

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Of Science and Technology
Ames, Iowa

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INTRODUCTION

Domestic livestock are, thermodynamically speaking, living unsteady-flow systems that are continuously transforming energy from the feed consumed into stored energy, heat and mechanical work. The first law of thermodynamics states the conservation of energy principle or that the increase in the energy stored in an open system is equal to the net transfer of energy into the system. Consequently, through the use of a basic energy balance, it would appear possible to predict the changes in performance of growing or producing animals resulting from different levels of air temperature. If this prediction could be done with sufficient accuracy it would be a valuable asset in design because it would substantially reduce the tedious experimental procedures now required. To investigate this concept was the basis for the work reported herein.

A true evaluation of the importance of the thermal segment in overall environment is dependent largely on how animals adjust to the various factors which comprise the thermal environment, i.e., factors that affect the regulation and balance of body heat. A warm-blooded animal can exist only within a limited range of body temperature, and a variation in body temperature of only a few degrees will cause serious effects. In order for the body temperature to remain constant, the system must be in a thermal steady state, in
which a balance is maintained between internal heat production and external heat loss to the surroundings. Homeothermic animals have complex chemical and physical controls which allow them to maintain a constant internal body temperature over a wide range of external thermal environments. However, the optimum thermal environment for an animal occurs when the heat produced internally is transferred to the environment without requiring adjustment of the homeothermic mechanisms from the optimum point.

The performance of the animal is greatly affected by the amount of heat exchanged between it and the environment. The heat losses from an animal may constitute 25 to 50 percent of the gross energy intake. In winter the heat loss to the surroundings increases and the heat produced during the digestion process and during maintenance may not be sufficient to balance the heat loss. As a result, net energy which would otherwise be utilized for growth or production is used to supply the additional heat needed to maintain a constant body temperature. This energy is wasted and represents a loss in production efficiency of the animal. In the summer the ease with which the animal can eliminate heat to its surrounding is decreased and any excess heat must be lost by evaporation of moisture from the respiratory tract and body surface. The rate of respiration increases and additional energy is expended internally which produces additional heat that must
be eliminated. Thus a stress condition results and the
animal reduces feed consumption to decrease the amount of
heat which must be dissipated to the environment. With the
reduction in energy input a decrease in growth or production
results.

It was previously indicated that a large percentage of
the total energy intake is transformed by animal and appears
finally as latent and sensible heat transferred to the
surroundings.

The transfer of sensible heat is governed by the
mechanisms of heat transmission by conduction, convection and
radiation. The animal has little control over these losses
of heat except by changing the blood supply to the skin, by
piloerection, and by altering body position. These sensible
heat losses are thus highly dependent upon the environment,
and almost entirely independent of the feeding level.

All animals dissipate significant amounts of latent heat
by evaporating moisture from their skin and respiratory
passages. The animal exerts considerable control over the
evaporation of water, i.e., the loss of heat by evaporating
water will be minimized under cold conditions and increased
under hot conditions.

Factors that affect an animal's rate of heat loss or gain
are temperature, vapor pressure and velocity of the ambient
air, and surface or radiant temperatures of the surroundings.
Air temperature is the most important single environmental factor. It is also the only climatic element that directly affects all four methods of heat transfer.

Growing Finishing Swine

Research over the past several years has shown swine to be quite responsive to air temperature. In just the past few years many swine producers have changed from pasture to various types of building and pen confinement housing systems. The trend in swine production in the United States is now toward a specialized business with large volume, low labor, and more capital invested in buildings and equipment for raising hogs in temperature controlled confinement. Swine production is of specific importance to Iowa, the nation's leading State in swine production.

There is little doubt that swine are being housed in confinement primarily to protect them from climatic extremes even though this also facilitates the daily management and thus reduces labor costs. Confinement is also beneficial in areas of the country where land formerly diverted to pasture is both suitable and more valuable for growing other crops.

Rather recently, some of the building manufacturers began fabricating and selling complete packaged units for confinement production of swine. These units usually feature an insulated and lined building, mechanical ventilation, automatic feeding systems, slotted floors with liquid manure disposal and long
narrow pens for small groups of animals. Some manufacturers advertise that the reduction in feed costs will more than pay for the increased investment in buildings and equipment and base these advertising claims on research results which indicate that a substantial improvement in the performance of swine can be obtained by controlling the air temperature within an optimum zone. However, these research results are often from experiments using small numbers of animals and of very short test periods, and may not correctly apply to commercial systems.

It is generally accepted that air temperature is the environment factor which has the greatest singular effect on the performance of growing-finishing swine. The extent to which air temperature should be artificially controlled if based on maximum economy for swine production is still an unknown factor. In other words, the cost of providing the optimum air temperature for growth over a lesser control may not be justified in relation to the added return obtained by the improved animal performance.

The range of air temperature to which growing-finishing swine can be exposed without great loss of production efficiency may be greater than indicated by the laboratory research. Thus the benefits obtained by utilizing buildings and equipment to provide a partial control that tempers only the extreme low or high temperatures and permits some daily
variation in the air temperature should be investigated carefully. The producer would then know, before investing large amounts of capital in specialized buildings and equipment, not just the optimum growth temperature but also the most economical temperature range for raising hogs in confinement.

If the economic advantage that may result from producing swine under partially controlled temperatures is to be determined, the effect of air temperature upon the performance of growing-finishing pigs must be known. Experimental means now being used to find temperature effects are long, tedious, and expensive. To find the influence of a single variable at one level requires a large number of pigs on test over a 5-month period.

Therefore, because of the importance of swine in the agricultural economy of Iowa, the availability of more than normal experimental data, the apparent typical response of these animals to temperature, and the fast increasing interest in controlled environment housing, growing-finishing swine were selected to test the prediction hypothesis by the following procedure:

1. Develop an unsteady-flow open-system energy balance equation applicable for growing or producing animals.

2. Simplify the general energy equation to theoretically predict the change in energy utilization of confinement-reared growing-finishing swine caused by a variation
of the air temperature from an arbitrary base level.

3. Obtain experimental data on the effects of air temperature on energy utilization of growing-finishing swine.

4. Compare results using experimental data with those of the theoretical analysis.

5. Predict the effect of air temperature on the performance of growing-finishing swine.
REVIEW OF AIR TEMPERATURE EFFECTS ON GROWING-FINISHING SWINE

It has been only in the past few years that interest and activity appeared in research to find the influence of environment on swine production. The effect of air temperature on growth rate and feed conversion of growing-finishing swine has been the single measure most studied under controlled environmental conditions. Also most of the reported experiments are application studies, designed to investigate economical methods that may beneficially modify naturally existing environments.

It seems to be generally accepted throughout the literature that air temperature is the environmental factor which has the greatest single influence on swine. However, the various research results are not in complete agreement as to the magnitude of the differences which occur in performance of growing-finishing swine raised under various levels of air temperature. There is a definite lack of complete correlation between the laboratory results and those measured under actual production conditions. No evidence could be found where the experimental results were related to estimates of energy transfer. Therefore the research summarized here is pertinent only as background to this study.

Heitman et al. (17) have conducted a number of basic experiments where environmental conditions were controlled within a psychrometric chamber. Each experimental test period was only
7 days in length and the same animals were used for alternate high and low temperatures without time between tests for acclimatization with regard to the effects of a constant air temperature upon gain and feed utilization. They found that for pigs weighing between 70 and 144 pounds, the optimum temperature was approximately 75°F. For pigs weighing between 166 and 260 pounds, the optimum temperature was approximately 60°F. Air temperatures above or below the optimum markedly lowered daily gains and increased feed required per unit of gain, indicating a very decided and precise optimum temperature for pigs.

Two Danish researchers, Sorensen and Moustgaard (27) conducted tests in a climatic laboratory to find the effect of constant air temperature on growth rate, feed utilization and carcass quality of growing-finishing pigs. Maximum growth rates and feed utilization were obtained from pigs kept at 15°C (59°F) with a relative humidity of 70% and at 23°C (71.6°F) with 50% relative humidity respectively. At 3°C (37.4°F) and a relative humidity of 70% and also at 24°C (75.2°F) with a 90% relative humidity, growth rate was decreased. The pigs kept at the lower temperature required the most feed per unit of gain. The carcass quality was best for pigs raised at 15°C and at lower or higher air temperatures less protein and more fat were deposited. From results obtained in studies on the protein deposition and thyroid
function of pigs, these same researchers concluded that a change of ambient temperature required a 3 to 4 week acclimatization period before the pigs again responded normally.

Bianca and Blaxter (1) summarized the results of five recent series of European experiments investigating the effects of environmental temperature on weight gain of fattening pigs. The results indicated that the effects of environmental temperatures within a rather wide range of temperatures from 12 to 23°C (53.6 to 71.6°F) on gain were small, probably less than 50 gm. per day. Also the maximal efficiency of feed conversion occurred within a similar broad range of air temperature.

Sorensen (26) reported that feed utilization, growth, and carcass quality in growing pigs (40 - 90 Kg) exposed to diurnal variations of temperature between 4°C and 14°C (39.2°F and 57°F) appeared to be approximately the same as that of a constant temperature which was close to the mean value of the fluctuating temperature.

Bond et al. (5) found that when the average of diurnally cycling temperature was near 70°F, the daily weight gains and feed conversion rates were more favorable at a constant temperature of 70°F than when air temperature cycled between 50 to 90°F or 40 to 100°F, but that a smaller diurnal variation in air temperature (60 to 80°F) did not greatly reduce the production efficiency of growing-finishing swine over that
obtained at a constant air temperature of 70°F.

Hazen et al. (13) found that the average air temperature at the hog level is a reliable index for predicting production efficiency of swine raised in confinement. They also found that the pigs over 100 pounds raised in confinement under varying temperatures gained 0.05 pounds per day less and required an additional 0.05 pounds of feed per pound of gain for each degree F of average temperature rise in the range of 80 to 85°F. However, practically no differences in feed efficiency or gain were found with 50 to 150 pound pigs in the range of 35 to 40°F.

The importance of the microclimate within swine buildings has been shown by results from an experiment reported by Sorensen (26). The pigs were divided into three groups, one without litter, one with straw for litter, and one group was kept in individual pens without litter. The air temperature in each space was 37.4°F. The performance of the pigs in pens with bedding corresponded rather closely to that of pigs kept in pens without litter but at a temperature of 48.2°F. The growth rate, feed conversion ratio and thyroid function were considerably more affected when the pigs were penned separately than when given the opportunity to huddle together.

Mount (23) investigated the effects of huddling on the heat production of young pigs and found that grouped pigs huddled together and were able to maintain a normal rectal
temperature at a lower energy cost than that required for individually penned pigs. The saving in energy expenditure was proportionately greater as the ambient temperature decreases from the thermoneutral range.

Muehling and Jensen (24) conducted tests to study the effect of environment on performance of young pigs weaned at 2 to 2½ weeks of age. Their results showed that elevating temperature by supplementary heating did not significantly increase growth rate above that of pigs exposed to a constant temperature of 38°F. However, more feed was required per pound of gain for the pigs without supplementary heat. In these tests the pigs were provided with ample bedding and kept free of drafts and dampness.

The importance of increased evaporation for relief of heat stress may be seen from experiments performed by Heitman and Hughes (16) in which pigs were housed at an air temperature of 100°F. In these experiments, the respiration rate dropped from 150 to 75 breaths per minute within 20 minutes after the floor of the pen was wetted with water; a fall in body temperature was also noted.

Culver et al. (7) designed a study to evaluate the effectiveness of water sprays and a hog wallow on the cooling of swine and upon the rate of gain in a normal fluctuating summer environment in market hogs. Three experiments involving a total of 120 pigs weighing from 85 to 220 lbs. were conducted.
In two of the experiments a mist-type spray significantly increased the rate of gain over the control group. In the control group, swine at complete rest beneath an open shade with a painted white wooden roof, rectal temperature and respiration rate rose with increasing ambient temperature.

Bond (3) summarized a series of tests conducted during the summers of 1955 through 1962 at Davis, California, to investigate various means of using water to provide relief for growing-finishing pigs stressed by hot weather. He reported that no significant benefits were found in weight gains of pigs by cooling the drinking water. Wallows were effective in increasing weight gains as much as 0.26 lbs. per day. Although feed required per pound of gain was apparently lower when wallows were available this could not be tested statistically. Sprays were as effective as wallows if judged by weight gain. Shading sprays was of no benefit. A continuous spray during the hot part of the day was more beneficial than one operating periodically. Mist-type sprinklers produced a spray that was too fine to be effective.

Heitman et al. (15) reported results of an experiment involving 48 growing-finishing pigs in confinement under California summer conditions where the average diurnal temperature ranged from 58.5 to 94.4°F with an average mean temperature of 75°F. The following treatments were compared to a control lot with only a shade: wallow in the sun,
wallow in the shade, wallow combined with increased air motion, access to a small air-conditioned house, and confinement to a pen inside a large swine barn. Over the 70-day experimental period all treated groups gained at a faster rate (1.43 to 1.51 lbs. per day) than the controls (1.30 lbs. per day), but there were no significant differences between treatments. Feed utilization appeared poorest in the control group and best in the group with access to the air-conditioned house.

Garrett (9) reported on hogs raised in two small houses, 6 x 14 x 4.5 feet, where the inside temperature was maintained at about 70°F with 2-ton air conditioners. Free access to or from the houses was permitted but feed and water for one pen of 8 pigs was located inside whereas the other group had to leave the building for feed and water. The control treatment was a similar pen with a shaded wallow. The average 24-hour temperatures outside during the test periods was about 90°F. No significant differences in daily gain, carcass yield or backfat thickness could be attributed to air conditioning even though each year the mechanically cooled hogs gained 0.1 pounds more per day than control animals. Placing the feed and water inside the house was without effect on daily gain of the air conditioned hogs, but daily feed consumption was 0.4 pounds higher and feed required per pound of gain was 0.18 pounds more when the feeder was located inside the house.

Edwards (8) states an objective in raising pigs is to
get the animals to market in the shortest possible time with
the minimum amount of feed which yields a quality carcass.
In a survey of the housing and production efficiency on 38
English farms he found that the pigs confined in a fully
enclosed house required less feed per pound of gain than those
housed in open-fronted sheds with outside yards. Approximately
0.5 pound of feed less was needed per pound of gain in winter
and 0.14 pounds of feed less during summer. He reported that
growing-finishing pigs should be housed at average temperatures
of 60 to 65°F and the indoor variation in temperature should
be less than half the daily variation outside.

Heitman and Moore (18) reported on California tests
comparing three types of housing for growing-finishing swine.
One house was totally enclosed and fully insulated, a second
was an extension of the insulated house but only partial
sidewalls, and the third was a shed closed only on one side.
Three tests were conducted to include winter, spring and
summer weather. Air and black globe thermometer readings
indicated pigs in the open shed were exposed to temperatures
with a greater range of diurnal variation than in either
of the other two houses. Both the rate of gain and feed
conversion were significantly less favorable, and the carcass
grade poorer, for pigs in the open shed compared with those
in either the enclosed house or its extension.
Recapitulation

The lower limit of the optimum temperature interval in which the best performance of growing-finishing swine is obtained appears to be approximately 55°F and the upper limit about 75°F. The effects of an unfavorable climate upon the performance of pigs may continue for a period of 3 to 4 weeks after the conditions have been improved. Therefore, it is necessary to distinguish between effects caused by a sudden drop in air temperature lasting a short period of time, and effects caused by exposure to air temperatures over so long a period that the animal may become acclimatized.

Natural variations of temperature occur under actual production conditions which can reduce or increase stresses for intervals of varying duration as compared with conditions of constant temperature. The several investigations of the diurnal air temperature effects upon growing-finishing swine give conflicting results indicating that further work is needed. The effects of diurnal variations of air temperatures on the performance of pigs appear to be similar to results obtained under a constant air temperature equal to the average of the varying temperature environment if limited to a daily variation of about 20°F.

Numerous studies on growing-finishing swine have investigated the benefits obtained from various methods of environmental control or modification. When the environmental
temperature is cold, pigs huddle together and reduce the effective surface area from which heat is lost. Thus, the unfavorable influence of low environmental temperatures on the economy of swine production is reduced by the insulating effect of the pigs huddling together and by the use of bedding materials in the pens. Under natural conditions pigs attempt to counteract the effect of a hot climate by wallowing in mud or water. This probably affords some cooling due to evaporation of water from the surface of the pig. Both water sprays and wallows are simple and effective methods for relieving high temperature stress since either promotes cooling by skin evaporation.
GENERAL ENERGY BALANCE FOR AN ANIMAL

Brody (6) made a comparative study of the energetic efficiencies and the influencing factors associated with the production of milk, meat, eggs, and muscular work. In his reports he discusses some of the principles of thermodynamics and their relationship to the energy transformations in living things, and develops formal analogies between nutrient and thermodynamic categories. He states that the first law of thermodynamics holds true for living as well as for nonliving systems; thus the sum of the energy equivalent of work performed by an animal, the energy in the production, the maintenance energy of the animal, and the heat increment of feeding must equal the energy generated from the oxidation of nutrients.

Perhaps then, additional thermodynamic techniques used in the solution of engineering problems involving inanimate systems would be both applicable and helpful in describing the energy utilization in animals.

Of specific interest in this work are (a) the development in detail of an unsteady-flow open-system energy balance equation applicable for animals, and (b) to appropriately simplify the equation to theoretically predict the differences in energy utilization of growing-finishing swine resulting from deviations of the air temperature from a reference or base condition.
Figure 1 is an energy and mass flow diagram for an animal. The boundaries are drawn to include the entire animal and the resulting energy balance, based on the first law of thermodynamics, is

\[ \frac{dQ}{d\theta} - \frac{dW}{d\theta} = \frac{dE}{d\theta} - \sum (n \frac{dM}{d\theta})_{\text{input}} + \sum (n \frac{dM}{d\theta})_{\text{output}} \]

A nomenclature of the terms in the basic energy balance for an animal is given in Table 1.

Table 1. Symbols for basic energy balance

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>( \frac{dQ}{d\theta} )</td>
<td>Rate of heat transfer by radiation, conduction, convection and evaporation from body surface if water is applied to surface.</td>
</tr>
<tr>
<td>( \frac{dW}{d\theta} )</td>
<td>Rate work is performed by animal on the surroundings.</td>
</tr>
<tr>
<td>( \frac{dE}{d\theta} )</td>
<td>Rate of change of the energy stored in the animal.</td>
</tr>
<tr>
<td>( \sum (n \frac{dM}{d\theta})_{\text{input}} )</td>
<td>Rate of enthalpy entering system.</td>
</tr>
<tr>
<td>( \sum (n \frac{dM}{d\theta})_{\text{output}} )</td>
<td>Rate of enthalpy leaving system.</td>
</tr>
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</table>

All terms are evaluated for a consistent interval of time \( d\theta \); for example, one day. A fundamental assumption is that the body is in a state of thermal equilibrium at all times. Thus the temperature of any given part of the system remains constant in time.
Figure 1. Mass and energy flow diagram for an animal.
Symbols used in the expansion and simplification of Equation 1 are defined in Table 2.

Table 2. Symbols for general energy balance

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>(c_f)</td>
<td>Specific heat of the feed</td>
</tr>
<tr>
<td>(c_p)</td>
<td>Specific heat of the air</td>
</tr>
<tr>
<td>(c_w)</td>
<td>Specific heat of the water</td>
</tr>
<tr>
<td>(e_f)</td>
<td>Gross energy of the feed</td>
</tr>
<tr>
<td>(e_h)</td>
<td>Heat increment of feeding</td>
</tr>
<tr>
<td>(e_m)</td>
<td>Net energy used for maintenance</td>
</tr>
<tr>
<td>(e_n)</td>
<td>Net energy of the feed</td>
</tr>
<tr>
<td>(e_p)</td>
<td>Net energy used for production</td>
</tr>
<tr>
<td>(e_u)</td>
<td>Metabolizable energy of the feed</td>
</tr>
<tr>
<td>(h_f)</td>
<td>Enthalpy of feed</td>
</tr>
<tr>
<td>(h_{kg})</td>
<td>Latent heat of vaporization of water</td>
</tr>
<tr>
<td>(h_p)</td>
<td>Enthalpy of products produced</td>
</tr>
<tr>
<td>(h_r)</td>
<td>Enthalpy of refuse</td>
</tr>
<tr>
<td>(h_w)</td>
<td>Enthalpy of water</td>
</tr>
<tr>
<td>(\frac{dM_a}{d\theta})</td>
<td>Mass rate of dry air inspired and expired</td>
</tr>
<tr>
<td>(\frac{dM_f}{d\theta})</td>
<td>Mass rate of feed intake</td>
</tr>
<tr>
<td>(\frac{dM_p}{d\theta})</td>
<td>Mass rate products cross system boundary</td>
</tr>
</tbody>
</table>
Table 2 (Continued)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{dM_r}{d\theta} )</td>
<td>Mass rate of refuse discharged</td>
</tr>
<tr>
<td>( \frac{dM_v}{d\theta} )</td>
<td>Mass rate of water vapor production</td>
</tr>
<tr>
<td>( \frac{dM_w}{d\theta} )</td>
<td>Mass rate of water intake</td>
</tr>
<tr>
<td>( \frac{dQ_n}{d\theta} )</td>
<td>Rate net energy available for production is used to maintain constant body temperature</td>
</tr>
<tr>
<td>( \frac{dQ_t}{d\theta} )</td>
<td>Total rate heat is lost to surroundings</td>
</tr>
<tr>
<td>( t_a )</td>
<td>Temperature of the air</td>
</tr>
<tr>
<td>( t_b )</td>
<td>Body temperature of the animal</td>
</tr>
<tr>
<td>( t_f )</td>
<td>Temperature of the feed</td>
</tr>
<tr>
<td>( t_w )</td>
<td>Temperature of the water</td>
</tr>
</tbody>
</table>

An arbitrary datum or reference state is selected for the evaluation of the enthalpies of the several energy sources entering and leaving the system. Then for any other state, the enthalpy relative to the datum is

\[
H = (H - H_0) + H_0
\]

The enthalpy is the sum of the reference value and any change in enthalpy between the reference and the given state. A convenient temperature reference is the internal body temperature which is assumed to be constant for a specific
animal. If the enthalpy is equated to zero at the reference state, the enthalpy value at any other state then becomes the change in enthalpy between the known and reference state. The final energy balance is obtained by combining the enthalpy relationships for the various components which are flowing into and out of the system.

First considered are the feed entering the system and the refuse, consisting of the feces, urine and any combustible gases produced in the digestive tract leaving the system. Figure 2 is an enthalpy-temperature diagram for the feed and refuse. Included in Figure 2 are some of the terms used by animal nutritionists to describe the various measures of the feed energy which in turn are related to the various differences in enthalpy being considered. A convenient reference state is the body temperature of the animal, all water in the liquid phase and all combustibles completely burned.

A unit mass of feed has an enthalpy \( h_f \), the exact value of which depends on the heat of combustion or gross energy \( e_f \), the constant pressure specific heat \( c_f \) and the temperature \( t_f \) of the feed. In Figure 2 the quantity \( (H_1 - H_a) \) represents the energy which must be supplied by the animal to change the feed to the body temperature of the animal \( t_b \). The enthalpy change \( (H_1 - H_2) \) represents heating value of the feed at constant pressure and the combination of these two enthalpy changes gives the enthalpy
Figure 2. Enthalpy-temperature diagram for feed, water and refuse.
of the feed referred to the internal body temperature as

\[ (3) \quad \dot{h}_f \dot{M}_f = (H_a - H_2) = (H_1 - H_2) - (H_1 - H_a) \]

The total rate of energy input in the feed consumed is

\[ (4) \quad \dot{h}_f \frac{d\dot{M}_f}{d\theta} = e_f \frac{d\dot{M}_f}{d\theta} - c_f (t_b - t_f) \frac{d\dot{M}_f}{d\theta} \]

Since the waste products leave the system at the datum temperature \((t_b)\) the enthalpy in the wastes is attributable to the heat of combustion of the undigested material in the feces, combustible gases and the digested nutrients excreted in the urine. The enthalpy leaving the system in the refuse in terms of Figure 2 is represented by

\[ (5) \quad \dot{h}_r \dot{M}_r = (H_b - H_2) \]

Also to be included in the reactant system is the water which the animal drinks and which is assumed to be originally at a lower temperature. The animal must provide heat to warm the water to the body temperature and the enthalpy of the water from Figure 2 becomes

\[ (6) \quad \dot{h}_w \dot{M}_w = (H_e - H_2) \]

and the rate heat is supplied to the water is

\[ (7) \quad \dot{h}_w \frac{d\dot{M}_w}{d\theta} = c_w (t_w - t_b) \frac{d\dot{M}_w}{d\theta} \]

Some animals have energy output in the production of milk, eggs, wool, etc. which either crosses the system boundary or is removed from the surface. For these animal systems the
total energy transferred in the products is given by the term

\[ \frac{dM_p}{d\theta} \]

Of these, the small amounts of energy which leave the system as perspiration, epidermal scales, and shed hair are not included in this development since they are normally small by comparison and cause no significant error if neglected.

Figure 3 is an enthalpy-temperature diagram for the mixture of dry air and water vapor entering and also leaving the system. In the respiration process the expired air is considered to be heated to the body temperature of the animal and almost saturated with water vapor. Since the initial temperature of inspired air rarely is equal to or above that of the body, or is this air in a saturated state, breathing results in a heat loss from the body through a warming and saturating of the inspired air in the lungs. The energy required to increase the temperature of the water vapor in the inspired air to the body temperature is small by comparison and therefore neglected.

Even though the chemical content of the inspired and expired air may differ, the specific heat \( c_p \) does not vary appreciably with the composition change or with temperature in the range under consideration and is assumed constant for this development. Also the mass of dry inspired air is considered to be equal to the mass of dry expired air.
Figure 3. Enthalpy-temperature diagram for inspired and expired air-water vapor mixtures.
From the foregoing assumptions, therefore, the energy lost in the respiration process now is

\[(9) \quad (H_f - H_2)_{\text{air}} + (H_2 - H_g) + (H_n - H_2)\]

which is the enthalpy change of the dry air plus the changes in enthalpy of the water vapor entering and leaving the system. Term 9 can be written

\[(10) \quad c_p (t_a - t_b) \frac{dM_a}{d\theta} + h_r \frac{dM_v}{d\theta}\]

The completed general energy equation for an animal can be written initially as

\[(11) \quad \frac{dQ}{d\theta} - \frac{dW}{d\theta} = \frac{dE}{d\theta} - e_r \frac{dM_f}{d\theta} + c_f (t_b - t_r) \frac{dM_f}{d\theta} + h_r \frac{dM_r}{d\theta} + h_p \frac{dM_p}{d\theta}, c_w (t_w - t_b) \frac{dM_w}{d\theta} + c_p (t_a - t_b) \frac{dM_a}{d\theta} + h_r \frac{dM_v}{d\theta}\]

The heat of combustion or gross energy of the feed used in the general energy balance equation has little nutritional significance since it does not indicate the energy which is utilized by the system. The animal nutritionist separates the heat of combustion of the feed into the unavailable energy which will be lost in the refuse and the metabolizable energy (\(e_u\)) which is the energy actually available from the feed for transformation by the animal. The metabolizable energy or the heat of reaction for the feed consumed is equal to the heat of combustion of the feed minus the heat of combustion for the refuse. From Figure 2
\[ e_u \frac{dM_f}{d\theta} = (H_1 - H_b) = (H_2 - H_1) - (H_b - H_2) \]

Therefore, the total rate of metabolizable energy input in the feed consumed is given by
\[ e_u \frac{dM_f}{d\theta} = e_f \frac{dM_f}{d\theta} - h_r \frac{dM_r}{d\theta} \]

The animal nutritionist does not usually consider that the metabolizable energy of the feed is materially influenced by either the daily feed intake or weight gains of the animal. Therefore, in this development the metabolizable energy of the feed is assumed to be a constant per unit of feed intake and independent of the amount of feed intake or growth rate of the animal.

The metabolizable energy of the feed is divided into the heat increment of feeding and the net energy which are given from Figure 2 by Equations 14 and 15 respectively.
\[ e_h \frac{dM_f}{d\theta} = (H_c - H_b) = (H_2 - H_1) - (H_b - H_2) \]
\[ e_n \frac{dM_f}{d\theta} = (H_1 - H_c) = (H_2 - H_b) - (H_c - H_b) \]

The heat increment of feeding or "specific dynamic action" is waste heat which results from the many intermediate and side reactions and oxidations incident to the nutritive processes, and which must be eliminated from the animal regardless of the external conditions.

Brody (6) indicates that the magnitude of the heat
increment of feeding of a nutrient is not a constant but highly variable depending on the reference base employed, balance between nutrients, plane of nutrition, environmental temperature, muscular or other productive activity, age, and so on. The results and theories found in the literature concerning the heat increment of feeding are contradictory and quantitative relations defining heat increment of feeding are non-existent. Therefore in this analysis for lack of better information the heat increment of feeding is considered to be a constant per unit of feed consumed.

The net energy of the feed is defined as that part of the gross energy retained in the animal for useful purposes, such as maintenance, growth, milk production, egg production, or muscular work.

The net energy is further subdivided into net energy for maintenance and production. The internal maintenance processes of circulation, respiration, secretion, and muscle tension produce no permanent effect on the surroundings of the animal. Therefore, the energy expended for the internal mechanical and chemical activities of the system is converted to heat and forms part of the heat outgo of the body. Thus the portion of net energy in the feed expended for maintenance is considered to be equal to the amount of heat produced by a fasting animal under thermoneutral conditions and is represented in Figure 2 by the enthalpy change
The net energy for production is defined as the energy appearing in weight gains, milk, eggs, wool, work and other products above normal maintenance costs. It normally is measured by the classical "difference trial" in which energy retention is determined at two levels of feed consumption above maintenance. The increase in energy retention brought about by the increase in feed intake is the net energy for production of that quantity of feed.

The net energy available for production from Figure 2 is given by

\[(17) \quad e_p \frac{dM_f}{d\delta} = (H_1 - H_d) = (H_1 - H_2) - (H_d - H_2)\]

Equation 17 can be written as

\[(18) \quad e_p \frac{dM_f}{d\delta} = e_f \frac{dM_f}{d\delta} - \left( e_h \frac{dM_f}{d\delta} + e_m \frac{dM_f}{d\delta} + h_r \frac{dM_f}{d\delta} \right)\]

The total rate of heat exchange between an animal and the surrounding environment is given by Equation 19. The heat lost includes the exchange by conduction, convection, radiation, evaporation of moisture from the body surface, and heat lost during the respiration process.

\[(19) \quad \frac{dQ_t}{d\delta} = \frac{dQ}{d\delta} + c_p (t_a - t_b) \frac{dM_a}{d\delta} - h_f g \frac{dM_v}{d\delta}\]

Substitution of Equations 18 and 19 into Equation 11 gives the following simplified general energy balance for an animal.
The first three terms appearing in Equation 20 now are combined and replaced by a single energy term, $\frac{dQ_n}{d\theta}$, which represents the difference between the rate heat is lost to the surroundings and the rate energy is converted into heat internally from the heat increment of feeding and during the maintenance processes so that

$$\frac{dQ_n}{d\theta} = \frac{dQ_t}{d\theta} + e_h \frac{dM_f}{d\theta} + e_m \frac{dM_f}{d\theta}$$

The heat lost to the surroundings is arbitrarily considered as negative and energy converted into heat internally as positive.

In a thermoneutral environment the value of $\frac{dQ_n}{d\theta}$ approaches zero because equilibrium of heat loss and heat production occurs without the use of net energy available for production to physically or chemically regulate the body temperature. When exposed to cold temperatures, if there is otherwise insufficient heat produced to balance the heat lost to the surroundings, the value of $\frac{dQ_n}{d\theta}$ is negative and the animal must produce additional heat by chemical body temperature regulation processes that oxidize body fuel. This additional heat is obtained from net energy otherwise available for production which causes a reduction in efficiency of the animal.
In the presence of high temperatures, the animal experiences increased difficulty in eliminating the internally produced heat at a rate sufficient to keep the body temperature constant. Consequently net energy from the feed otherwise available for production may be used instead for physical temperature regulation by increased blood circulation, higher respiration rate, etc., which increase the rate of heat transfer to the surroundings.

The general energy balance of Equation 11 for an animal now is reduced to

\[
\frac{dQ_n}{d\theta} - \frac{dW}{d\theta} = \frac{dE}{d\theta} - e_p \frac{dM_f}{d\theta} - c_f (t_f - t_b) \frac{dM_f}{d\theta} + \frac{dM_p}{d\theta} - c_w (t_w - t_b) \frac{dM_w}{d\theta}
\]

which is the form pertinent to this study.
ENERGY UTILIZATION OF GROWING-FINISHING SWINE

The general energy balance, Equation 22 needs to be modified for specific application to growing-finishing swine. In this section the necessary modifications are discussed and use is made of the resulting equations to predict differences in animal performance caused by difference in environmental temperature. Additional terms used are defined in Table 3.

For growing-finishing swine no production crosses the system boundary. Therefore, the term from Equation 22 which gives the energy utilized for production is zero.

$\frac{dM_p}{dh} = 0$

Table 3. Symbols for energy utilization

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{dW_g}{d\theta}$</td>
<td>Rate of gain in body weight</td>
</tr>
<tr>
<td>$E$</td>
<td>Efficiency (ratio of weight gained to the feed consumed)</td>
</tr>
<tr>
<td>$e_b$</td>
<td>Energy content of body weight gained</td>
</tr>
<tr>
<td>$\Delta E$</td>
<td>Difference in efficiency</td>
</tr>
<tr>
<td>$\Delta M_f$</td>
<td>Difference in rate of feed intake</td>
</tr>
<tr>
<td>$\Delta Q_n$</td>
<td>Difference in rate net energy is utilized to keep body temperature constant</td>
</tr>
<tr>
<td>$\Delta Q_t$</td>
<td>Difference in rate of heat loss</td>
</tr>
<tr>
<td>$\Delta W_g$</td>
<td>Difference in rate of weight gained</td>
</tr>
</tbody>
</table>
The difference in the energy utilization by confinement-reared growing-finishing swine which results between those raised at an arbitrary reference or base temperature ($t_o$) within the thermoneutral temperature range and another air temperature level ($t_1$) is determined by subtracting each term of the energy balance for the base ($t_o$) from the corresponding energy balance for condition $t_1$. The following results

\[
\left( \frac{dQ_{nl}}{d\theta} - \frac{dQ_{no}}{d\theta} \right) - \left[ \frac{dW_{1}}{d\theta} - \frac{dW_{C}}{d\theta} \right] = \left[ \frac{dE_{1}}{d\theta} - \frac{dE}{d\theta} \right] - [e_p \frac{dM_{fl}}{d\theta} - e_p \frac{dM_{fo}}{d\theta}] - c_f \left[ (t_{fl} - t_b) \frac{dM_{fl}}{d\theta} - (t_{fo} - t_b) \frac{dM_{fo}}{d\theta} \right] - c_w \left[ (t_{wl} - t_b) \frac{dM_{wl}}{d\theta} - (t_{wo} - t_b) \frac{dM_{wo}}{d\theta} \right]
\]

To simplify Equation 24 the following limiting conditions are assumed:

(1) The mechanical work performed by confinement-reared growing-finishing swine on the surroundings during their daily activities is small. Work is done when the pigs move their bodies from the floor to a standing position and during the respiration process, when the surface of the pigs move the surrounding air. The daily activities of pigs differ somewhat with various levels of air temperature. However, the difference in mechanical work performed by pigs at different air temperatures is considered to be insignificant and the term $\left( \frac{dW_{1}}{d\theta} - \frac{dW_{C}}{d\theta} \right)$ is neglected.
(2) The difference between the heat required to warm the water consumed to body temperature in each ambient temperature condition is given by

\[ dM_{\text{w}} \text{(25)} = c_w \left[ (t_{w1} - t_b) \frac{dM_{w1}}{d\theta} - (t_{w0} - t_b) \frac{dM_{w0}}{d\theta} \right] \]

Values for Term 25 were calculated from the daily water intake of pigs of several weights, a constant internal body temperature of 102.5°F, and the assumption that the water temperature was related to air temperature by Equation 26 for the range of air temperature from 30 to 90°F.

\[ (26) \quad t_w = 15 + \frac{2}{3} t_a \]

If the daily water intake for a given weight of pigs is assumed to be the same at all temperatures, differences between the heat required per hour to warm the water are plotted in Figure 4 for pigs weighing 50 and 200 pounds. These differences in heat required are minor with respect to the differences in total heat loss and energy intake which occur and are neglected in this work.

In the buildings used to collect experimental data a circulating water system provides water of the same temperature to all of the animals. Thus, if the daily water intake is considered to be the same at all levels of air temperature the difference in heat required by the experimental animals to warm the water to the body temperature is zero.
Figure 4. Estimated effect of air temperature on the rate heat is utilized by pigs for warming consumed water.
The difference between the rates heat is used by pigs housed at different air temperatures to warm the feed to the body temperature is given by

\[ (27) \quad \frac{dM^f_1}{d\theta} = \left( (t_{f1} - t_b) \frac{dM^f_1}{d\theta} - (t_{fo} - t_b) \frac{dM^f_0}{d\theta} \right) \]

Values for Term 27 were estimated with the assumptions that the specific heat of the feed was 0.45 Btu per pound per °F, and the feed temperature was equal to the average air temperature which surrounds the feeder. The average daily feed consumptions given by Hays (11) were used as the base values of \( \frac{dM^f_0}{d\theta} \) for pigs weighing 30 and 200 pounds.

The feed consumption at air temperatures higher and lower than the base temperature of 60°F is estimated by Equation 28 for air temperatures from 30 to 90°F. Thus for every degree below or above 60°F the feed consumption was assumed to increase or decrease one percent respectively.

\[ (28) \quad \frac{dM^f_1}{d\theta} = [1.6 - \frac{t_{al}}{100}] \frac{dM^f_0}{d\theta} \]

The maximum differences, both positive and negative, which might be expected in the energy utilized by pigs to warm the feed to their body temperature are plotted in Figure 5 for pigs weighing 30 and 200 pounds. Term 27 produces negligible values in comparison with the other differences in energy utilization which occur.

Equation 24 for predicting the change in energy utilization
Figure 5. Estimated effect of air temperature on the rate heat is utilized by pigs for warming consumed feed.
is now simplified to

\[ \left[ \frac{dQ_{nl}}{d\theta} - \frac{dQ_{no}}{d\theta} \right] = \left[ \frac{dE_1}{d\theta} - \frac{dE_0}{d\theta} \right] - \left[ e_{pl} \frac{dM_{pl}}{d\theta} - e_{po} \frac{dM_{po}}{d\theta} \right] \]

The above relationship indicates that the major differences in energy utilization of growing-finishing swine, which occur between levels of air temperature, are a change in net energy intake, difference in the energy stored as body weight, and variation in the heat loss.

The difference in energy intake now is

\[ \left[ e_{pl} \frac{dM_{pl}}{d\theta} - e_{po} \frac{dM_{po}}{d\theta} \right] \]

The net energies per unit of feed intake available for production at the air temperature level \( t_1 \) and the base temperature \( t_0 \) are \( e_{pl} \) and \( e_{po} \) respectively. If the feed is the same for both temperature levels and the average net energy is assumed to be constant and independent of air temperature, level of feed consumption and growth rate, then

\[ e_{pl} = e_{po} = e_p \]

The terms \( \frac{dM_{pl}}{d\theta} \) and \( \frac{dM_{po}}{d\theta} \) are the mass rates of feed intake for the temperature conditions \( t_1 \) and \( t_0 \) and the difference is replaced by \( \Delta M_f \) which represents variation in feed consumption.

Term 30 becomes

\[ \left[ e_{pl} \frac{dM_{pl}}{d\theta} - e_{po} \frac{dM_{po}}{d\theta} \right] = e_p \Delta M_f \]
The change in energy stored in body weight is represented by the term

\[ \frac{dE_1}{d\theta} - \frac{dE_0}{d\theta} \]  

(33)

A knowledge of the chemical composition of the body gains is needed for precise evaluation of the amount of energy stored and this would vary per unit of gain with body weight. However in the equation a unit of body weight gained by a pig of a given weight is assumed to have an average energy value \( e_b \) for purposes of simplification.

Then Term 33 can be written

\[ e_{bl} \frac{dW_{g1}}{d\theta} - e_{bo} \frac{dW_{go}}{d\theta} \]  

(34)

For further simplification the energy value of the weight gained, when the animals are self-fed the same rations, is assumed independent of air temperature, growth rate of animals, and level of feed intake. Then,

\[ e_{bo} = e_{bl} = e_b \]  

(35)

The rate of weight gained at the temperatures \( t_o \) and \( t_1 \) are \( \frac{dW_{go}}{d\theta} \) and \( \frac{dW_{g1}}{d\theta} \) respectively and their difference is expressed as \( \Delta W_g \). Then Term 34 can be written as

\[ e_{bl} \frac{dW_{g1}}{d\theta} - e_{bo} \frac{dW_{go}}{d\theta} = e_b \Delta W_g \]  

(36)

The difference between the amount of net energy available for production which is utilized by growing-finishing swine to
maintain a constant body temperature is written as

\[
\frac{dQ}{d\theta} = \frac{dQ_n}{d\theta} + \frac{dQ_{no}}{d\theta} = \Delta Q_n
\]

Equation 24 now reduces to

\[
\Delta Q_n = e_b \Delta W_g - e_p \Delta M_f
\]

Equation 38 as developed for growing-finishing swine to predict the effect of air temperature on energy utilization indicates that the major differences which occur will be dependent on the heat loss, energy input, and energy stored.

For the work in this thesis the efficiency of growing-finishing swine is defined as the ratio of the weight gained to the feed consumed. Thus,

\[
E = \frac{dW}{d\theta} / \frac{dM_f}{d\theta} = \frac{dW}{dM_f}
\]

The difference in efficiency between pigs raised at air temperature \( t_0 \) and temperature level \( t_1 \) is given by Equation 40.

\[
\Delta E = E_1 - E_0 = \left( \frac{dW}{dM_f} \right)_1 - \left( \frac{dW}{dM_f} \right)_0
\]

The weight gained and feed consumed at temperature \( t_1 \) also can be expressed in terms of similar measures at temperature \( t_0 \) as

\[
\frac{dW}{d\theta} = \frac{dW}{d\theta} + \Delta W_g
\]

\[
\frac{dM_f}{d\theta} = \frac{dM_f}{d\theta} + \Delta M_f
\]
Equation 38 gives the predicted relationship between $\Delta W_g$ and $\Delta M_f$ which is substituted along with Equations 41 and 42 into Equation 40. The difference in efficiency is expressed in terms of the differences between the heat loss and feed intake of pigs raised at $t_1$ and $t_o$, and the estimated average growth rate and feed consumption of the control group at $t_o$.

\[
\Delta E = \frac{dW_{go} + \Delta Q_n e_b + (e_f/e_b) \Delta M_f}{dM_{fo} + \Delta M_f} - \frac{dW_{go}}{dM_{fo}}
\]

The effects of air temperature on the efficiency of growing-finishing swine are not constant. Equation 43 indicates that the difference between the efficiency of pigs housed at $t_1$ and the animals housed at $t_o$ depends on the differences in the heat loss and feed consumption. It appears possible that efficiencies could be equal for both temperature levels.

Solutions for Prediction Equations

The evaluation of the prediction Equations 38 and 43 requires selection of values for the net energy of the feed available for production, energy content of the weight gained, and differences in net energy utilized to maintain a constant body temperature. Also values for the daily gain and feed intake of pigs of various weights housed at the base air temperature $t_o$ must be estimated to predict differences in efficiency.

The energy content of a pound of body weight gained by pigs of various body weights has been estimated by Mitchell
and Kelley (20), and values are plotted in Figure 6. The data indicate that the fat content in the composition of body weight gains of swine increases with age and thus the energy content increases and the gain per unit of feed input decreases as the animal increases total body weight. Mitchell (21) experimentally measured the energy values of the composition of growth gains of growing and fattening Duroc-Jersey swine. These values, also plotted in Figure 6, gave higher values for the energy content of pig gains than did the original estimate. The average of these two estimates was used for $e_b$ in the equations developed in this thesis which predict the changes in energy utilization of growing-finishing swine caused by differences in air temperature.

The net energy values of various feed ingredients given by Morrison (22) were used to estimate the average net energy available in the ration for production. The estimated average net energy value selected was 800 calories per pound of ration. The net energy values of growing-finishing swine rations for production were not found in the literature reviewed and the value used is questionable.

The average metabolizable energy values of swine rations given by Hays et al. (10) are listed in Table 4 for various weights of growing-finishing swine. Considering the value selected for the productive net energy approximately 60 percent of the metabolizable energy is available for production,
Figure 6. Estimated energy content of weight gained by growing-finishing swine.
which is a reasonable value for swine rations.

Table 4. Average metabolizable energy contents of growing-finishing swine rations

<table>
<thead>
<tr>
<th>Type of Ration</th>
<th>Weight of Pigs (lbs)</th>
<th>Metab. Energy (Cal/lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18% pig starter</td>
<td>10 to 30</td>
<td>1388</td>
</tr>
<tr>
<td>16% pig grower</td>
<td>30 to 50</td>
<td>1332</td>
</tr>
<tr>
<td>14% complete G-F</td>
<td>50 to 125</td>
<td>1368</td>
</tr>
<tr>
<td>12% complete G-F</td>
<td>125 to 220</td>
<td>1398</td>
</tr>
</tbody>
</table>

Values for the net energy normally available for production at thermoneutral conditions which growing-finishing pigs housed at other temperatures utilize to maintain a constant body temperature were not found in the literature reviewed. The difference between the net energy available for production which is utilized by growing-finishing swine raised at temperatures $t_0$ and $t_1$ for maintaining a constant body temperature is written

\[
\frac{dQ_{n1}}{d\theta} - \frac{dQ_{no}}{d\theta} = \left[ \frac{dQ_{t1}}{d\theta} - \frac{dQ_{tc}}{d\theta} \right] + e_n \left[ \frac{dM_{f1}}{d\theta} - \frac{dM_{fc}}{d\theta} \right] + \left[ e_m \frac{dM_{f1}}{d\theta} - e_{mo} \frac{dM_{fc}}{d\theta} \right]
\]

The total net energy utilized by animals for maintenance is measured under thermoneutral conditions and the values for pigs of a given weight should be equal and thus the difference is assumed to be zero. To evaluate Equation 44 the total rates of heat loss from animals at different air temperatures
should be measured under production conditions where a reference feed intake has been established for a given weight of animal and maintained at all temperature levels. Therefore the difference between the heat loss of animals at the reference temperature and other temperatures is uncomplicated by heat increments of feeding and the difference in net energy available for production which is utilized to maintain a constant body temperature can be evaluated. Then as the feed intake changes between growing-finishing pigs at the reference temperature and pigs at other air temperatures the difference in heat increment of feeding can be included in the analysis. The difference in the total rates of heat loss is expressed as $\Delta Q_t$ and Equation 44 becomes

\begin{equation}
\Delta Q_n = \Delta Q_t + e_n \Delta M_f
\end{equation}

Recent investigations into the heat and moisture production of swine have been conducted at the Davis, California, Psychrometric Chamber. Bond et al. (4) measured the total heat loss under constant temperature conditions over the range of 40 to 100°F and expressed their findings by the regression equation

\begin{equation}
Y = 2.477 + 0.034 X_1 - 0.577 X_2 + 0.148 X_1^2 + 0.710 X_2^2
- 0.313 X_1 X_2
\end{equation}

where

$Y = \log$ total heat loss, Btu per hour
Equation 46 was used to calculate the rates of heat loss for growing-finishing swine raised at temperature levels in the range of 30 to 90°F. The application of Equation 46 to predict heat loss rates below 40°F may be questionable, but other values were not available. An air temperature of 60°F was selected for the reference temperature. The differences in the rates of heat loss of several weights of growing-finishing swine housed at air temperatures deviating from 60°F are shown in Figure 7.

The heat loss measurements by Bond et al. (4) were not based on the same feed intake at all temperature levels and the differences between the rates of heat loss include various heat increments of feeding. Therefore the values calculated for $\Delta Q_t$ were used for $\Delta Q_n$ and the term for the heat increment of feeding was not included in the subsequent analysis.

Prediction equations were developed for various weights of pigs and programmed on an IBM 7074-1401 computer system. An example of the prediction equation and the computer output for the predicted differences between the daily gain of pigs weighing 50 pounds housed at 60°F and littermates at other temperatures in the range of 30 to 90°F is illustrated in Appendix A. The predicted values for 25, and 100 pound

\[ X_1 = \log \text{body weight, pounds} \]
\[ 100 X_2 = \text{air temperature, } ^\circ F \]
Figure 7. Effect of air temperature on the rate of heat loss from growing-finishing swine.
growing-finishing pigs result in the family of curves plotted in Figures 8 and 9. These theoretical curves indicate the effect of air temperature on the growth rate of growing-finishing swine depends greatly on the difference in feed consumption between the temperature levels. Therefore, it appears that unless the difference in feed intake ($\Delta M_f$) is fixed for a given difference in air temperature the difference in growth rates ($\Delta W_g$) would not be constant but a series of values. The curves indicate also that the growth rate of pigs raised in confinement with air temperatures below $60^\circ F$ would be the same as at the $60^\circ F$ base condition if the feed consumption was increased at these lower temperatures. In fact, if feed intake was increased sufficiently then the rates of daily gain could be greater at the lower temperatures than at $60^\circ F$.

The average daily feed consumptions and daily gains of growing-finishing swine given by Hays (11) were used as the base values of $\frac{dM_f}{d\phi}$ and $\frac{dW_g}{d\phi}$ in Equation 43 developed to predict differences in efficiency between pigs housed at $60^\circ F$ and other levels of air temperature. An example of the application of Equation 43 and computer output of the predicted differences between efficiency of pigs weighing 50 pounds is also illustrated in Appendix A. Figures 10 and 11 are example plots of the differences in efficiency estimated for growing-finishing swine weighing 25 and 100 pounds respectively.
Figure 8. Predicted effects of air temperature and feed intake on the rate of weight gained by pigs weighing 25 pounds.
Figure 9. Predicted effects of air temperature and feed intake on the rate of weight gained by pigs weighing 100 pounds.
Figure 10. Predicted effects of air temperature and feed intake on the efficiency of pigs weighing 25 pounds.
Figure 11. Predicted effects of air temperature and feed intake on the efficiency of pigs weighing 100 pounds.
These predicted values indicate that the difference between efficiency of growing-finishing swine resulting from a given difference in air temperature is not constant but a series of values could occur depending on the differences in the feed intake.

Summary

The basic energy balance for animals, Equation 22, was modified for application to growing-finishing swine. With subsequent simplifications, Equation 38 developed. It indicates that the major differences between the amount of energy stored by growing-finishing pigs housed at a reference air temperature \( (t_o) \) and littermates exposed to another temperature, \( t_1 \), will depend on the rates of heat loss and the energy inputs in the feed consumed. Equation 43 predicts the differences between the efficiency of feed energy utilization in terms of the efficiency of pigs at temperature, \( t_o \), and the differences between the rates of heat loss and feed intake of the animals housed at the reference temperature and littermates raised at \( t_1 \).

Air temperature directly influences the rate of heat exchange between growing-finishing swine and the surroundings. At air temperatures below the thermoneutral zone the rate of heat loss is greater and the pigs may be required to utilize energy normally available for growth to produce additional heat to maintain a constant body temperature. Subsequently if the
feed intake is equal for pigs at both temperatures the rate of gain and efficiency of pigs at the colder air temperature will be less. However, if the appetite of the pigs at the colder temperature increases the additional feed intake may supply sufficient energy to balance the additional heat loss and the rate of weight gained may be the same as at the warmer temperature.

The pigs housed at temperatures above the thermoneutral zone experience difficulty in eliminating the heat internally produced at a rate sufficient to maintain a constant body temperature. The appetite of the pigs will undoubtedly be reduced and as the feed intake declines the waste heat which must be transferred to the surroundings will decrease. Subsequently, the reduction in feed intake decreases the net energy available for production and the growth rate would be less than for pigs housed at the reference temperature.

The entire theoretical analysis indicates that the response of growing-finishing swine to different air temperatures in terms of differences in liveweight gain and efficiency of feed energy conversion will not be constant if feed intake is not directly related to, and predicted by, a change in air temperature.
EXPERIMENTAL

Introduction

A series of six experiments involving a total of 612 pigs was conducted to determine the differences in performance which occur between growing-finishing swine raised in confinement under various levels of air temperature. The initial set of three experiments, was conducted during the summers of 1959 and 1960 and the winter of 1959-60. The second set of three tests was conducted during the summer of 1961 and the winters of 1960-61 and 1961-62. Although all tests were directed primarily toward a study of the effects of air temperature, associated information was also gathered on the possibility of counteracting undesirable levels of air temperature by modifying the protein content of the ration. More specifically, the second set of tests included information on the interrelationships between air temperature and protein level in the ration and feed efficiency, rate of gain and carcass quality. The results concerned with the effects of protein have been discussed by Seymour et al. (25).

The results from all six experiments were used to investigate the validity of the theoretical equation developed earlier in this thesis. Deviations in daily gain, feed consumption and efficiency that occur with growing-finishing pigs when the air temperature differs from a base condition of 60°F were experimentally measured and used in the development
of empirical prediction equations.

Buildings and Equipment Used for Experiments

The basic buildings and equipment used for these experiments were developed by Hazen (12) and remodeled by Mangold (19). Briefly, the facilities for the fluctuating air temperature studies were nine windowless 4-pen hog houses oriented in a single line on the Swine Nutrition Farm of Iowa State University (Figure 12). The prefabricated houses, 16 by 20 feed in plan, were insulated, lined with aluminum sheets and equipped with heating and ventilating equipment. The three centrally located buildings were additionally equipped with 4-ton refrigeration units which provided sufficient cooling capacity to maintain the buildings at a constant temperature of approximately 60°F (Figure 13). These three units provided the common temperature base to which the performance of all the different other groups of experimental animals were compared.

The six remaining houses were divided into two equal groups and the space air temperature was controlled with differential thermostats to fluctuate in a pattern corresponding to the normal air temperature pattern outside, but at levels approximately 10°F and 20°F respectively above the mean outside air temperature.

The mean outside temperature normally expected for Ames, Iowa, was obtained from U.S. Weather Bureau records and the
Figure 12. Exterior view of 4-pen hog houses. Inner nine units used for housing animals.

Figure 13. Arrangement of equipment within constant temperature buildings.
ARRANGEMENT OF EQUIPMENT WITHIN CONSTANT TEMPERATURE BUILDINGS (G-4, G-5, & G-6)
initial three experiments scheduled so that environmental control during the major portion of the tests could be accomplished with heating and ventilating equipment. This procedure permitted maximum control with a moderate equipment expenditure.

In the second series of three experiments eight houses were used to provide a statistical design with four replications of two temperature treatments. Consequently a fourth building was equipped with refrigeration equipment for year-around control of the air temperature at approximately 60°F. In the non-refrigerated buildings the differential thermostats were removed and heating thermostats installed so that constant temperatures of about 90°F could be maintained during the summer with heating equipment. In the winter tests the air temperature within these four buildings was permitted to vary as before with the temperature outside.

Management of Animals

All of the pigs in the experiments were obtained from the swine nutrition farm breeding herd and predominantly of crossbred breeding. Each pig was weighed, ear notched and given an iron injection within 24 hours after birth. The male pigs were castrated at approximately five days of age. All pigs received injections of modified hog cholera virus and antiserum and erysipelas bacterin at seven weeks of age.
Weaned pigs were placed in the test houses when approximately three weeks of age. The following week was used to permit pigs to adjust to the new surroundings and to become acclimatized to the test temperature. The pigs were randomly allotted from littermate outcome groups to a split plot design of experimental treatments. During the first three experiments the pigs were subjected to three test periods, each approximately five weeks in length, with a statistically predetermined realloation and a one week reacclimatization at the end of the first and second five week periods. The animals and feeders were weighed at the beginning, after three weeks, and at the end of each test period. The protein level of the self-fed complete ration was changed at the end of the first and second test periods (Appendix B).

During the other three experiments the pigs remained in the same pen until marketed at approximately 200 pounds body weight. In the winter experiment of 1960-61, there were four temperature treatments as the level of air temperature in half of the houses was reversed when the pigs reached an average of 125 pounds. In the last two experiments there were only two temperature treatments and the pigs remained at the same temperature level throughout the experiment. The ration treatments are presented in Appendix B. The pigs and feeders were weighed on two or three week intervals until some of the pigs reached market weight and then the animals of 195
pounds or more were weighed and marketed weekly.

The pigs had unrestricted access to self-feeders and to special float-controlled waterers that provided water of essentially the same temperature in all houses. Since the buildings had exposed uninsulated concrete floors, wood shavings were used for bedding so that the results were dependent upon air temperature within the pens and not upon slab temperature.

The buildings and pens were cleaned and disinfected before the initiation of each experiment. During the course of each experiment the pens were cleaned daily.

Air Temperature Records

Thermographs and hygrothermographs were used to obtain continuous records of the air temperature at a level six inches above the floor near the back of the center alley in each building. This location had been checked previously and found to give readings that were representative of air temperatures existing in the pens at the animal level. At the end of each week the charts were replaced and average weekly air temperatures were determined from the planimetered areas.

The extremes in average weekly air temperature in the control houses varied from a low of 52°F during a week when the average outside temperature was 5°F to a high of 64°F in the summer when the outside temperature averaged 80.5°F. There were shorter periods of time during the six experiments when equipment malfunction permitted a greater temperature
variation but these caused no observable detrimental effects.

General Observations

Because the behavior of the animal does conceivably affect his heat transfer, following are some pertinent observations made on the animals and their activities during this study:

1. The pigs exposed to the high temperatures during the summer (80°F and above) attempted to counteract the hot conditions by keeping the floor wet with liquids from the waterers and from body wastes and laying prone separated from other animals a major portion of the time (Figure 14). Thus, evaporation of moisture from the surface of the pigs may have helped the animals increase heat loss and reduce temperature stress. The pigs subjected to hot conditions were extremely dirty while the pigs in the buildings cooled to 60°F remained very clean during the experiments (Figure 15). The pigs exposed to the constant 60°F kept a portion of the pen dry and free of body wastes for laying down. Thus the cleanliness of pigs raised in confinement in pens with solid concrete floors is influenced to a large extent by the level of air temperature. Clean water in the form of sprays during periods of high temperature in the summer may be used to help reduce temperature stress and keep pigs raised in confinement from wallowing in the wastes.

2. The young pigs (4-9 weeks of age) which were subjected
Figure 14. Typical pen of pigs housed at 90°F. Note dispersion of pigs and dirty haircoats.

Figure 15. Typical pen of pigs housed at 60°F. Note activity of pigs and clean haircoats.
to cold air temperatures moved the wood shavings used for bedding to the corners of the pens and huddled close together (Figure 16). Besides reducing the surface area of the pigs which was exposed to the surroundings, this probably increased slightly the temperature of the air which surrounded the pigs thus reducing the heat loss. Even the heavier pigs when subjected to cold temperatures spent a large amount of time crowded close together (Figure 17). The pigs housed in the low temperature buildings during the winter grew longer hair coats, which lacked the glossy "show pig" appearance of the control group maintained at 60°F, thus thermal conductivity of the hair coats of the pigs at cold air temperatures probably was less than the animals at 60°F.

Summary of Experimental Data

Each of the six experiments was subdivided into three test periods varying in length from three to five weeks. Average pig weights for the three periods were approximately 30, 75 and 140 pounds. The experimental values measured were the feed consumption, gain in body weight and average air temperature at the hog level. A representative sample of the collected data, taken from one of the six experiments, is presented in Appendix C. Performance comparisons, summarized in this section, are referenced to like values obtained from animals housed at 60°F.
Figure 16. Typical pen of young pigs housed at 45°F. Note tendency to huddle together.

Figure 17. Typical pen of pigs weighing 50 pounds housed at 35°F. Note rough haircoats and tendency to huddle together.
Calculated for the three test periods were the differences in daily feed consumption, daily weight gain and efficiency in converting feed to body weight gain, which resulted between pens of three pigs raised at the reference condition of approximately 60°F and their littermates housed at other air temperatures. To reduce the scatter among plotted points on the figures in this section, the differences were calculated on a house basis so that each point represents an average of the differences between four pens of three pigs. The differences between individual pens of three pigs were used for calculating linear regression equations to show the trends and to determine if the differences were statistically significant. An example of the least squares analysis is presented in Appendix D.

Effects of air temperature on feed consumption

The differences in the daily feed intake which resulted between pigs raised at a reference temperature of 60°F and littermates housed at other temperature levels are shown in Figure 18 for the three average weights of pigs. The mean value of the differences in daily feed intake for each temperature level investigated also is shown on the plots.

The experimental results indicate that the average daily feed intake became less than the intake at 60°F when the average air temperatures reached approximately 72, 74 and 70°F, respectively, for the 30-, 75- and 140-pound pigs. As the air
Figure 18. Experimental effects of air temperature on the feed intake of growing-finishing swine.
DIFFERENCE IN FEED INTAKE (LBS/PIG/DAY)

PERIOD III
PIGS (107 to 170 LBS)

\[ \Delta M + 0.0064 - 0.0005A \]
\[ r^2 = 0.045 \]

PERIOD II
PIGS (65 to 95 LBS)

\[ \Delta M + 0.0048 - 0.0063A \]
\[ r^2 = 0.4410 - 0.001 \]

DIFFERENCE IN FEED INTAKE (LBS/PIG/DAY)

WINTER TESTS
1981-82

SUMMER TESTS
1969

PERIOD I
PIGS (40 to 49 LBS)

\[ \Delta M + 0.0065 - 0.0004A \]
\[ r^2 = 0.0010 - 0.04 \]
temperature increased further, the daily feed intake per pig decreased approximately 0.005, 0.04 and 0.05 pounds per °F increase for the three weights of pigs.

The regression coefficients for the linear equations relating feed intake and positive air temperature deviations were significant for the second and third test periods.

At air temperatures below 60°F, no significant differences in the feed intake were measured. Even though in several cases it was slightly less, in general, feed intake under the cold temperature conditions was equal to or greater than at 60°F.

**Effects of air temperature on rate of gain**

The effect of air temperature on the daily weight gain of growing-finishing swine is shown separately in Figure 19 for the light, medium and heavy weight pigs. At the higher temperatures where feed intake declines, a reduction in the daily weight gained also occurs. The decline in daily gain of 0.005, 0.01, and 0.015 pounds per °F increase above approximately 72°F for the 30-, 75- and 140-pound pigs, respectively, all were highly significant.

The effect of air temperatures lower than 60°F on the daily gain of the experimental animals was variable, paralleling the feed intake of the pigs. In general, the rate of gain was less for the pigs housed at air temperatures colder than 50°F if the animals were eating less or approximately the
Figure 19. Experimental effects of air temperature on the rate of weight gained by growing-finishing swine.
DIFFERENCE IN RATE OF WEIGHT GAINED (LBS/PIG/DAY)

\[ \Delta W = -0.195 + 0.0006 T \]

\[ r = -0.42 \]

\[ p < 0.05 \]

DIFFERENCE IN RATE OF WEIGHT GAINED (LBS/PIG/DAY)

\[ \Delta W = -0.04 + 0.0002 T \]

\[ r = -0.137 \]

\[ p > 0.05 \]

DIFFERENCE IN RATE OF WEIGHT GAINED (LBS/PIG/DAY)

\[ \Delta W = -0.03 \]

\[ p > 0.05 \]
same quantity of feed consumed by those at 60°F. If the feed intake was substantially higher at the colder temperatures, the rate of gain was about equal to or higher than that at 60°F. The decline in daily gain for 140-pound pigs of 0.015 pounds per °F decrease below approximately 48°F was highly significant.

Effects of air temperature on efficiency

The changes in the efficiency of growing-finishing swine, expressed as pounds of weight gain per pound of feed consumed, with deviations of air temperature from the 60°F reference are shown in Figure 20 for the three test periods. The efficiencies of growing-finishing swine housed at temperature levels at 70°F and above tend to be slightly higher than at 60°F. However, the differences in efficiency were not significant.

The efficiencies of pigs raised at air temperatures below 50°F were less desirable than at 60°F. The decrease in efficiency for the light and medium weight pigs approached significance at the 10 percent level. The efficiency decrease for heavy weight pigs as the air temperature decreased below 50°F of 0.002 pounds of gain per pound of feed intake for each °F decrease was highly significant.

The efficiency differences caused by temperature differences appears to be independent of animal size. Therefore, a composite plot of all mean values from the
Figure 20. Experimental effects of air temperature on the efficiency of growing-finishing swine.
three test periods for each temperature level investigated is shown in Figure 21. The efficiencies of growing-finishing swine raised at air temperatures above 60°F were not significantly different from the efficiencies of pigs housed at 60°F. However, the overall efficiencies of growing-finishing swine decreased 0.0016 pounds of gain per pound of feed intake for every °F decrease below about 57°F. Consequently, a pig raised from 15 pounds to 215 pounds at 37°F would require approximately 75 pounds of feed more to reach market weight than a littermate raised at 57°F.
Figure 21. Overall experimental effects of air temperature on the efficiency of growing-finishing swine.
ANALYSIS AND DISCUSSION OF RESULTS

The experimental differences in feed consumption and efficiency of daily gain which resulted between individual pens of three pigs raised at a base condition of 60°F and their littermates housed at other levels of air temperature were compared with the predicted differences. The preliminary plots of the differences in daily gain and efficiency versus the corresponding differences in feed intake showed large scattering and intermingling of the individual experimental points for the various temperature levels investigated. To increase the confidence in the experimental prediction equations the number of observations was increased by combining the three summer and three winter experiments into a series of plots for the three average weights of pigs and both positive and negative temperature differences. The overall average deviations in air temperature from 60°F were calculated for each plot. Thus only the overall effects of the various air temperatures investigated above or below 60°F could be evaluated and compared.

Summer Tests

The three summer test periods had overall average temperature differences from the reference of 60°F of +18.7, +24.0 and +21.1°F, respectively. The differences in average daily gain versus differences in daily feed intake are shown in
Figure 22 for the three summer test periods. Also shown are the mean values of the differences in daily feed intake and gain for each high temperature level investigated. The equations for the lines determined by linear regression and the correlation coefficients are given on the separate plots.

Under conditions of equal feed intake, the differences between the daily gain of growing-finishing swine housed at 60°F and at higher air temperatures were all slightly negative. For the young pigs, this small intercept value of -0.02 pounds of gain per day was significant. The intercept values for the other two test periods, however, were not significant. Therefore, it appears that the major differences found experimentally between the growth rate of growing-finishing swine housed at 60°F and at levels of air temperature above 60°F result because of variations in the daily feed intake. The average daily feed intake of the pigs during the second and third test periods housed at air temperature of 80°F and above was significantly less than the littermates at 60°F, and subsequently a significant decrease in the daily weight gained resulted.

The differences in efficiency of daily gain versus differences in daily feed intake that resulted for the three summer test periods are plotted in Figure 23. The linear regression equations indicate that as the feed intake decreases at the higher temperatures, the efficiency increases.
Figure 22. Effects of feed intake and air temperatures above 60°F on the rate of weight gained by growing-finishing swine.
Figure 23. Effects of feed intake and air temperatures above 60°F on the efficiency of growing-finishing swine.
DIFFERENCE IN EFFICIENCY (LBS GAIN/LB FEED)

-0.04
-0.02
0.00
0.02
0.04
0.06

DIFFERENCE IN FEED INTAKE (LBS/PIG/DAY)

-0.12
-0.08
-0.04
0.00
0.04
0.08
0.12

DIFFERENCE IN EFFICIENCY (LBS GAIN/LB FEED)

ΔE = 0.0075 - 0.0323(AM)
γ = +0.0522 (P < 0.05)

DIFFERENCE IN EFFICIENCY (LBS GAIN/LB FEED)

ΔE = 0.0015 - 0.0234(AM)
γ = +0.0468 (P < 0.05)

PERIOD I

MEAN Δ = 1.2 ± 0.6°F

PERIOD II

MEAN Δ = 1.1 ± 0.6°F

PERIOD III

MEAN Δ = 1.0 ± 0.6°F
for all three average weights of pigs studied. The regression coefficients for the last two test periods were highly significant, indicating that pigs housed at temperatures above 60°F decrease their feed intake and gain weight more efficiently than their littermates housed at 60°F.

The increment of weight gained by growing-finishing swine decreases for each successive unit of feed intake above the intake at 60°F. Thus if the energy of each unit of weight gained is constant, the utilization of feed energy must decrease as the feed intake increases and each succeeding increment of weight gained requires progressively more feed energy input.

Winter Tests

The three winter test periods had overall average temperature differences from the reference of 60°F of -15.2, -19.5 and -19.8°F, respectively. The differences between the average daily gain and feed intake of pens of three pigs housed under cold temperatures and their littermates at approximately 60°F are plotted in Figure 24. The equations for the lines determined by linear regression and the correlation coefficients are given. The regression coefficients or slopes of the equations were significantly different from zero for all three test periods. The differences in daily weight gained per pig for equal feed intake at the compared temperatures each was highly significant. Thus, air temperatures.
Figure 24. Effects of feed intake and air temperatures below 60°F on the rate of weight gained by growing-finishing swine.
below 50°F cause a reduction in the average daily gain of
growing-finishing swine when the feed consumption is the same
as that for pigs at 60°F. This indicates that pigs housed at
the colder air temperatures utilize energy for body temper­
ature regulation that is used for growth at 60°F.

When the daily feed intake was approximately 0.065,
0.50 and 0.90 pounds more per pig at the colder temperature
for the first, second and third test periods, respectively,
the daily gain was the same as at 60°F. Therefore, the
growth rate of pigs housed at 60°F and littermates confined
to colder air temperature can differ widely, depending on the
rate of feed intake.

The differences in efficiency of feed converted to weight
gain versus differences in feed intake for the three winter
test periods are shown in Figure 25. The differences in
efficiency varied greatly, but the major portion of the
differences in production efficiency were negative. The
differences which occur between the efficiency of growing-
finishing swine housed at 60°F and at lower air temperatures
when the difference in feed intake is zero were -0.017,
-0.026 and -0.024 pounds of gain per pound of feed for the
30, 75 and 140 pound pigs, respectively. These intercept
values were highly significant and indicate that, for the
same feed intake, pigs housed at temperatures below 60°F
gain significantly less per unit of feed than the control
Figure 25. Effects of feed intake and air temperatures below 60°F on efficiency of growing-finishing swine.
PERIOD I  
MEAN Δ \( T = 141.9^\circ \)F  
EXPERIMENTAL  
\( \Delta E = -0.0170 - 0.0102 \Delta M_f \)  
\( r = 0.088 \)  
-0.06  
-0.04  
-0.02  
0  
0.02  
0.04  
0.06  
DIFFERENCE IN FEED INTAKE (LBS/PIG/DAY)  
DIFFERENCE IN EFFICIENCY (LBS GM/LB FEED)  
-0.8  
-0.6  
-0.4  
-0.2  
0  
0.2  
0.4  
0.6  
0.8  
1.0  
PREDICTED

PERIOD II  
MEAN Δ \( T = 18.8^\circ \)F  
EXPERIMENTAL  
\( \Delta E = -0.0255 - 0.0022 \Delta M_f \)  
\( r = 0.33 \) (P<0.05)  
-0.06  
-0.04  
-0.02  
0  
0.02  
0.04  
0.06  
DIFFERENCE IN FEED INTAKE (LBS/PIG/DAY)  
DIFFERENCE IN EFFICIENCY (LBS GM/LB FEED)  
-1.0  
-0.5  
0  
0.5  
1.0  
1.5  
2.0  
2.5  
PREDICTED

PERIOD III  
MEAN Δ \( T = 19.8^\circ \)F  
EXPERIMENTAL  
\( \Delta E = -0.0239 - 0.0055 \Delta M_f \)  
\( r = 0.178 \)  
-0.06  
-0.04  
-0.02  
0  
0.02  
0.04  
0.06  
DIFFERENCE IN FEED INTAKE (LBS/PIG/DAY)  
DIFFERENCE IN EFFICIENCY (LBS GM/LB FEED)  
-3.0  
-2.0  
-1.0  
0  
1.0  
2.0  
3.0  
PREDICTED
animals at 60°F. The slopes of the regression equations for the three weights of pigs were -0.010, -0.012 and -0.006 pounds of gain per pound of feed and indicate that as the pigs housed at the colder air temperatures increase feed intake above reference the efficiency will decrease. The regression coefficients were, however, not significant.

Comparison of Prediction Equations

Theoretical equations were developed around numerical values closely representing the average body weights of the experimental animals and the differences in mean air temperature for each test period. The predicted differences in daily weight gained and efficiency expected for the experimentally found differences in daily feed intake are included on the plots of experimental data to illustrate the variations which exist between the theoretical and experimental equations.

The slopes and intercepts of the theoretical equations differ markedly from the experimental values but the variables recorded during the experimental tests, by themselves, do not give the exact reasons for the variations between the theoretical and experimental equations. Present indications are that rather expensive additional equipment and buildings will be required, with detailed measurements on the large number of pigs, before many of these reasons can be experimentally verified. However, the factors that could cause the variations are discussed here, and values which give
better agreement between the theoretical and experimental than those originally used to develop the prediction equations are suggested.

The slopes of the theoretical equations, calculated from the ratio of the net energy per pound of feed to the gross energy per pound of gain, are greater than the slopes from the experimental equations. To simplify the theoretical analysis, the net energy of the feed available for production was assumed to be constant. However, according to Brody (6), the net energy per unit of feed consumed is a function of the gross energy intake and decreases above the maintenance level with successive increments of feed intake. The differences in feed intake being considered in this analysis represent increments of feed that are above maintenance level. Therefore, better agreement between the theoretical and experimental relationships might be obtained if information were available to indicate the precise variation of the net energy of swine feeds with gross feed intake. If it can be assumed that the values used for the gross energy of the weight gained are applicable to the experimental animals, the slopes of prediction equations will agree with experimental slopes when the net energy of the feed, originally assumed to average 800 calories per pound, is decreased to approximately 670, 440 and 400 calories per pound for the incremental differences in feed consumption involved in the three test periods.
Figure 26 shows the effects of varying the net energy of the feed consumed per day for three weights of pigs averaging 45, 85, 145 pounds and when eating approximately 3, 5 and 7 pounds of feed per pig each day, respectively. If the average overall net energy per unit of feed consumed was 800 calories, the corresponding total net energy intake for the three weights of pigs would be 2400, 4000 and 5600 calories per day respectively. A second curve for each weight of pig is also shown in Figure 26 which considers the first two pounds of feed consumed to have a constant net energy per unit of feed and each additional increment of 2 pounds to decrease in value to 670, 440, and 400 calories per pound for the three weights of pigs.

Figure 26 indicates one possible reason why, for the medium and heavy-weight pigs, the slopes (pounds of gain per pound of feed) obtained from the experimental equations for cold temperatures were slightly less than slopes from equations for hot temperature levels (0.221 versus 0.246 and 0.163 versus 0.205) respectively. The daily feed intake of pigs exposed to hot temperatures was significantly less while the daily feed intake of pigs at cold temperatures was not significantly more than for the littermates housed at 60°F. Therefore, the net energy values applicable to the considered differences in feed intake would tend to be greater for the pigs eating less and the result would be more gain.
Figure 26. Estimated effects of feed intake on the net energy of the feed available for growth by growing-finishing swine.
per unit of feed consumed.

Better agreement between the slopes obtained with predicted and experimental equations also could be obtained if the average gross energy values of the gain used in the prediction equations were increased. However, the trend in swine breeding during the past 30 years since Morrison (22) measured the energy contents of pigs has been toward leaner pigs. Thus the energy values per unit of body weight gained by the experimental animals used in this work might be slightly lower than the values used in the theoretical analysis.

The theoretical analysis, for simplicity, assumed the gross energy content of the weight gained by growing-finishing swine to depend only on the body weight of the animals. However, this is not in complete agreement with data reported by Sorensen (26) which he obtained from chemical analyses of the complete carcasses of pigs weighing about 90 kilograms and raised under different climatic conditions. The average gross energy content estimated from the chemical composition of the pigs are shown in Table 5 for various temperatures and relative humidities. It appears that air temperature influences the gross energy content of growing-finishing swine. To compensate for differences which may occur between the gross energy per pound of weight gained by pigs housed at air temperatures other than 60°F, the difference in energy stored would be given by Term 34 rather than as simplified by Term 36.
Table 5. Estimated energy content of 90 kg. pigs

<table>
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<th>Temperature (°C)</th>
<th>Relative humidity (%)</th>
<th>Gross energy (Cals/lb)</th>
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</thead>
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<td>90</td>
<td>1823</td>
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<tr>
<td>23</td>
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<td>3</td>
<td>70</td>
<td>1733</td>
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</table>

The theoretical analysis predicted greater differences than occurred experimentally between the daily gain of growing-finishing pigs confined at temperatures below 60°F and littermates housed at 60°F, but with the same daily feed intake. The theoretical equation, as developed, considers that the differences between the heat lost to the surroundings from growing-finishing pigs raised at air temperatures differing from 60°F is net energy and thus represents potential growth. Therefore, the estimated differences between the heat loss of pigs housed at 60°F and at lower air temperatures which were calculated from relationships developed by Bond et al. (4) must be decreased if the intercepts of the theoretical equations are to closely predict the experimental values. As previously indicated, the differences between the heat loss may include differences in the heat increment of feeding which would cause the predicted differences in growth rate to be greater than the experimental differences.
The hogs in the work by Bond et al. (4) were kept at one temperature condition for only a seven-day period while the test periods for the experimental work reported in this thesis were from three to five weeks long. Sorensen (26) indicated that during the first week after a sudden fall in temperature the poorest protein utilization occurs and the weight gained is greatly less than the gains which subsequently occur as animals become acclimatized to the temperature level. Subsequently, the heat loss during the first week might be expected to be greater than for the following two to four weeks as animals adjust to their environmental temperature. Thus the average heat loss estimated for growing-finishing pigs from data based on a one-week test period may not be applicable where animals are being housed at one temperature level for longer periods of time.

Summary

The numerical coefficients in the theoretical prediction equations representing slopes and intercepts of the resulting plots differ considerably from the experimental values. In the theoretical equations the values for the differences in heat loss, average net energy of the feed available for production, and the gross energy for the weight gained were obtained from work by other experimenters and are not believed to be applicable for the animals used in the experiments reported in this thesis, even though the simplifying assumptions
made in the theoretical analysis could be responsible for some of the variation. It appears that the net energy available per unit of feed for production is not constant, but decreases with successive increments of feed intake above the maintenance level. Also the gross energy per pound of weight gained by pigs may not be constant, as assumed, for a given body weight but may vary with air temperature, relative humidity and the rate of feed intake. The rates of heat loss measured from growing-finishing pigs and secured from constant temperature test periods limited to one week may not be applicable for pigs raised at one air temperature for longer periods of three to five weeks, particularly if the latter permits a physiological adjustment to the environment. However, the linear theoretical equations for predicting the differences in rates of liveweight gained and the experimental equations agree as to general form. The theoretical analysis predicted that a series of differences can occur between the daily gain of pigs housed at 60°F and littermates confined at other temperature levels depending on the corresponding differences in daily feed intake. The experimental part also indicated that the effect of a given air temperature on the growth rate of growing-finishing swine is not constant but varies with changes in level of feed consumption.
The primary objective of the work reported in this thesis was to investigate both analytically and experimentally the effect of air temperature on the energy utilization of growing-finishng swine. The first law of thermodynamics was applied to an animal and a generalized unsteady-flow open-system energy equation was developed. This initial energy equation was then modified to predict the differences which occur between the energy utilization of pigs raised in confinement at a reference temperature of 60°F and their littermates housed at other air temperatures from 30 to 90°F. When certain simplifying assumptions were imposed, the theoretical analysis indicated that the major differences which occur in the energy utilized by growing-finishng swine exposed to various levels of temperature deviating from 60°F are differences in heat loss and energy intake. Subsequently with unlike amounts of energy available for storage, differences result in the growth rates and efficiencies (pounds of gain per pound of feed). The differences between the responses of growing-finishng swine to air temperature, both in terms of liveweight gains and efficiency of energy utilization, were predicted for several weights of pigs. The differences in the rate of weight gained and efficiency, predicted for a given deviation in air temperature from 60°F, varying depending on the difference in feed intake. Therefore, one physical reaction
of thermoregulation important to the energy utilization of growing-finishing swine is the effect of air temperature on the appetite of pigs.

Six experiments, involving a total of 612 pigs, were conducted to investigate the effects of air temperature on performance of growing-finishing swine and to check the validity of the prediction equations. Results of these experiments indicate that growing-finishing swine being fed ad libitum can be raised in a range of air temperatures from 50 to 75°F without significant differences in growth rate or efficiency. The daily feed intake of pigs exposed to air temperatures of 75°F and higher also was found to be consistently less than the feed intake of the pigs housed at 60°F. Subsequently the daily gain of the pigs at the higher temperature was less than for the pigs at 60°F but the weight gained per unit of feed was found to be slightly better.

Although the daily feed intake of pigs housed at air-temperatures below 60°F tended to be slightly higher than the feed consumption of the littermates housed at 60°F, the differences were not consistent, and in some of the test periods the feed intake was actually less at the colder temperatures. The increased feed consumption of the pigs at the cold temperatures, in a few tests, was sufficient to meet the increased rate of heat loss, and the growth rate was approximately the same as the pigs at 60°F. The growth
rate and the efficiency of pigs housed at air temperatures below 50°F generally were significantly less than the littermates at 60°F.

It appears that the differences in efficiency which occur between growing-finishing swine housed at various air temperatures is independent of the body weight of the pigs and can be related directly to the deviation in air temperature from 60°F.

Empirical plots were developed and linear regression equations were calculated relating the differences in the rate of weight gained and efficiency to the differences in feed intake which resulted between pigs raised at a reference temperature of approximately 60°F and their littermates housed at air temperatures above and below 60°F.

The regression coefficients for the equations comparing the differences in the rate of weight gained and feed intake were significant for all temperature differences. Thus, the differences which occur between the feed intake of pigs raised at different levels of air temperature have an important effect on the differences in growth rate which will result.

The regression coefficients for the equations comparing the differences in efficiency and feed intake indicate that growth rate of growing-finishing swine decreases for each successive increment of feed intake above maintenance. Therefore, since the feed intake of pigs housed at air temperatures above 75°F is less than for littermates at 60°F,
the energy utilized per unit of feed for growth will be higher and thus the efficiency is slightly better than at 60°F.

The general linear form of the experimental equations relating the differences in the weight gained and feed intake agree with the analytical equations although the coefficients differ markedly. The linear regression equations relating the experimental differences in efficiency and feed intake did not agree with the prediction equations except for young pigs raised at high temperatures. The values used in the theoretical analysis for the rate of heat loss, net energy of the feed available for growth and the gross energy of the weight gained by growing-finishing swine are questionable. Therefore, changes in these values would give better numerical agreement between the analytical and experimental equations.

It appears that further investigations are required before good agreement can be obtained between the analytical and experimental prediction equations. The more important of these are:

1. An experiment to investigate the net energy of feeds available for growth by various weights of growing-finishing swine for different levels of feed intake and determine if the net energy utilized for growth decreases with successive increments of feed intake.

2. Additional research to measure the gross energy stored in the weight gained by various weights of growing-finishing swine raised at various air temperatures and with
different rates of feed intake. Then the theoretical analysis might be expanded to predict the differences which may occur between the carcass quality of pigs raised at different temperatures if the overall differences in daily feed intake and weight gained are known from birth to market weight.

3. An investigation of the average heat loss of growing-finishing swine maintained at a given level of air temperature for periods of various lengths to determine if differences occur in the rate of heat loss as animals become acclimatized. Consideration should be given in the progress of this experiment to varying the feed intake of the animals to check for variations in heat production which might be due to differences in the heat increment of feeding.
REFERENCES CITED


ACKNOWLEDGMENTS

The author wishes to acknowledge and express appreciation for the guidance and understanding of the members of his graduate study committee composed of Dr. C. W. Bockhop, Dr. G. K. Serovy, Professor R. C. Fellinger, Dr. R. E. Untrauer, Dr. V. W. Hays and Dr. Thamon Hazen.

This thesis was prepared under the direction of Dr. Thamon Hazen whose continued encouragement and sound counsel are sincerely appreciated.

Appreciation is also extended to Dr. V. C. Speer and to Mr. Donald Baker and associates on the Swine Nutrition Farm staff for assistance in the experimental work.
APPENDIX A: SAMPLES OF PREDICTED DIFFERENCES
Figure 27. Predicted effects of air temperature and feed intake on the rate of weight gained by pigs weighing 50 pounds.
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**DIFFERENCE IN AIR TEMPERATURE**

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Figure 28. Predicted effects of air temperature and feed intake on the efficiency of pigs weighing 50 pounds.
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APPENDIX B: COMPOSITION OF BASAL RATIONS
Table 6. Composition of basal rations for varying temperature experiments

<table>
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<tr>
<th>Percent Protein</th>
<th>I 18%</th>
<th>II 15%</th>
<th>III 12%</th>
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</thead>
<tbody>
<tr>
<td>Ingredients</td>
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<td></td>
</tr>
<tr>
<td>Ground yellow corn</td>
<td>56.2</td>
<td>79.15</td>
<td>86.50</td>
</tr>
<tr>
<td>Solvent soybean oil meal (50% protein)</td>
<td>22.5</td>
<td>16.10</td>
<td>8.85</td>
</tr>
<tr>
<td>Dried Whey (70% lactose)</td>
<td>15.0</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>Stabilized lard</td>
<td>2.0</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>Calcium carbonate (33% Ca)</td>
<td>0.80</td>
<td>0.80</td>
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<tr>
<td>Dicalcium phosphate (26% Ca, 18% P)</td>
<td>0.85</td>
<td>1.35</td>
<td>1.25</td>
</tr>
<tr>
<td>Iodized salt</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Trace mineral premix (35-C-41)</td>
<td>0.15</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Vitamin-antibiotic premix (corn carrier)</td>
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<td>2.00</td>
<td>2.00</td>
</tr>
<tr>
<td>Total (lb)</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
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</table>
Table 7. Composition of basal rations for temperature-protein experiments

<table>
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<tr>
<th>Ingredient</th>
<th>3 to 7 wk</th>
<th>7 wk to 125 lbs.</th>
<th>125 to 200 lbs.</th>
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</thead>
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<tr>
<td></td>
<td>20%</td>
<td>16%</td>
<td>17%</td>
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<tr>
<td>Ground yellow corn</td>
<td>51.70</td>
<td>61.20</td>
<td>75.10</td>
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<tr>
<td>Solvent soybean oil meal (50% protein)</td>
<td>27.00</td>
<td>17.40</td>
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<tr>
<td>Dried whey (70% lactose)</td>
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<tr>
<td>Stabilized lard</td>
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</tr>
<tr>
<td>Calcium carbonate (33% Ca)</td>
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<td>.85</td>
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<tr>
<td>Dicalcium phosphate (26% Ca, 18% P)</td>
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<tr>
<td>Iodized salt</td>
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<tr>
<td>Trace mineral premix (35-C-41)</td>
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<td>.10</td>
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<tr>
<td>Vitamin-antibiotic premix (corn carrier)</td>
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<td>2.00</td>
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</tr>
<tr>
<td>Total (lb)</td>
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<td>100.00</td>
<td>100.00</td>
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APPENDIX C: EXAMPLES OF EXPERIMENTAL AND CALCULATED DATA
Table 8. Example of experimental data

<table>
<thead>
<tr>
<th>Avg air temp (°F)</th>
<th>Weight gained (lbs/day)</th>
<th>Feed intake</th>
<th>Avg air temp (°F)</th>
<th>Weight gained (lbs/day)</th>
<th>Feed intake</th>
<th>Avg air temp (°F)</th>
<th>Weight gained (lbs/day)</th>
<th>Feed intake</th>
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Table 9. Example of calculated data

<table>
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<tr>
<th>Deviation in air temp (°F)</th>
<th>Diff in weight gained (lbs/day)</th>
<th>Diff in feed intake (lbs/day)</th>
<th>Diff in efficiency (lbs gain/lb feed)</th>
<th>Deviation in air temp (°F)</th>
<th>Diff in weight gained (lbs/day)</th>
<th>Diff in feed intake (lbs/day)</th>
<th>Diff in efficiency (lbs gain/lb feed)</th>
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Summer 1959 - Test Period II
APPENDIX D: EXAMPLE OF REGRESSION ANALYSIS
Figure 29. Linear regression analysis for the second test period of the summer experiments.