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DUCT: A PC Program for Sizing and Evaluating Grain-Store Ducts[1]

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Abstract—In the past, seed-store ducts have usually been designed by use of velocity-limiting-rules and guess work, rather than by predictive methods. To make a predictive method accessible[1] to designers we have developed program DUCT. It is an easily used IBM[2] Personal Computer (PC) or PC compatible program that predicts velocity and pressure distributions, and determines duct flow uniformity and fan pressure load, for seed-store ducts. Program DUCT can also *find* the smallest duct *size* that achieves a specified flow uniformity, or, fan pressure load. This enables designers to readily *optimize* their duct design by finding the *smallest duct size* that achieves an acceptable flow uniformity or fan pressure load. This paper describes the features of program DUCT and considers some of the factors influencing selection of the program's input values.

Introduction

Previous Work

Computer models capable of predicting seed-store duct performance (see, for example, Shove and Hukill, 1963; Marchant and Nellist, 1977; Burrell et al., 1982), have existed for some time. However, these predictive models have not been made widely available to duct designers. Duct designers have therefore based their designs on velocity-limiting-rules (Shove; Brook, 1979; Navaro and Calderon, 1982; Hellevang, 1984). These rules attempt to maintain uniform duct flow by keeping duct longitudinal and face velocities below set limits. For common geometries such as rectangular or circular stores, a number of computer programs have recently become available (Bridges et al., 1988; Greenwood, 1988; Prive, 1989) that automate the use of these rules. Consequently, seed-store ducts continue to be designed using velocity-limiting-rules and *without predicting* the velocity and pressure drop distributions along the duct. Problems can arise from this approach, particularly for long ducts.

Aims

The main aims of this work are:

1. to make widely available[1] to duct designers an easily used IBM[2] Personal Computer (PC) or PC compatible computer program (program DUCT) that allows them to *predict* the air velocity and pressure distributions occurring along seed-store ducts; and

2. to set-up program DUCT to function as a *design tool* that allows designers to easily find the smallest (and cheapest) duct size needed to attain a specified duct flow uniformity, or fan

[1] **Program DUCT is available for purchase from SGRL.**
[2] **IBM is a trade mark of International Business Machine Corp.**

pressure load. Conventional predictive methods only evaluate the performance of a duct of *already* known duct-size and must be used iteratively to optimize duct size.

Features of the Program

Program **DUCT**:

- enables design of aeration and fumigation ducts,
- in vertical and horizontal seed-stores,
- of *any* floor plan and *any* duct lay-out; and
- applies to packed or unpacked seed and
- to suction *and* blowing ducts.

The program employs stable numerical methods that enable its calculations to take only a few minutes on a basic PC. The program includes an on-line help facility that explains how to select its input values. The program's User Manual expands on the material included in this paper, and explains how to design duct-layout.

The program also plots graphs to enhance the user's understanding of its results. These graphs show the variation of air pressure, and longitudinal and face velocities along the duct. The graphs, and all text output from the program, can be saved and printed. For blowing ducts in aeration systems, the program also calculates the temperature rise through the fan.

Tables 1 to 5 included in the program's User Manual (Wilson, in press) and in the programs on-line help, give values ebablingthe program to be used for a wide variety of grains, oilseeds, and legumes and for common seed-store and duct materials. The program applies to seven common duct geometries, these being:

- round ducts,
- half-round ducts,
- above floor rectangular ducts,
- in-floor rectangular ducts,
- split in-floor rectangular ducts,
- shedder plate ducts, and
- corner ducts.

Duct Flow Uniformity and Fan Pressure Load

Two factors that are very important to the design of ducts are:

1. the flow uniformity along the duct, and
2. the amount of pressure that the fan needs to generate in order to force the air along the duct and through the seed bulk. We call this pressure the fan pressure load.

1. *Duct Flow Uniformity,* τ—As air flows along a duct, some of it must also pass through perforations in the duct face to aerate or fumigate the seed bulk. The flow rate through the duct face is called the face velocity, u, m/s.

   Ideally, to ensure that seed at one end of the duct does not receive more aeration of fumigation treatment than seed at the other end, the face velocity should be the same at any point along the duct. This ideal of complete flow uniformity cannot be achieved unless the duct is very large and expensive, so, in practice, we usually strike a compromise by accepting a reduced flow uniformity in return for a smaller less expensive duct.

Program **DUCT** calculates the duct flow uniformity, τ, - (that is, dimensionless[3]), as

$$\tau \equiv \frac{u_{min}}{u_{max}}, \tag{1}$$

where the subscripts ***max*** and ***min*** indicate the largest and smallest u values, respectively, that occur along the duct.

Velocity-limiting methods of duct design do not allow you to determine the duct flow uniformity and this is precisely why they can cause problems in design of long ducts.

2. *Fan Pressure Load,* $\mathcal{F}$—The fan pressure load arises from two sources:

   (a) The pressure drop caused by the height of the seed that the air passes through. This pressure drop is unavoidable and is the *minimum* possible fan pressure load, $\mathcal{F}_{min}$.

   (b) The pressure drop caused by constriction of the flow field around the duct. This value is effected by the size of the duct.

   Program **DUCT** takes into account both of these pressure drops and allows you to use a search mode (explained below) to optimize the pressure drop caused by flow constriction.

Evaluation and Search Modes

There are two situations commonly faced by duct designers:

1. For existing ducts, they need to *evaluate* whether those ducts are suitable for a particular application.

2. When designing new ducts, they need to be able to *find* the optimum *size* needed to achieve satisfactory duct performance.

To meet these needs, program **DUCT** can be used in two modes:-

1. *Evaluation mode*—finds the duct flow uniformity, τ, and fan pressure load, $\mathcal{F}$, Pa, that occur for a specified duct cross-sectional area, A, m^2. You can use evaluation mode to decide if *existing* ducts are adequate or would be useful in new circumstances.

2. *Search mode*—determines the smallest duct area, A, needed to attain a specified τ value, *or,* a specified $\mathcal{F}$ value. As above-floor duct costs increase at somewhere between the square and the cube of the duct width, even small reductions in duct size can give considerable cost savings. You can use search mode to *design new* ducts.

   After the search, program **DUCT** allows you to interactively choose, from duct sizes you have available, a size nearest to that found by the program's search. The program will then evaluate the performance of the chosen duct size.

Below, in the section titled "How to Optimize Duct Design," we explain how to use search mode.

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[3] **As each new variable is introduced, its dimensions (that is, its units) are also given. Where a variable is dimensionless, this is indicated by a hyphen, -.**

Selection of Input Values

Treatment Rate (of air or fumigant)

We use the term treatment rate to refer to the flow rate of aeration air or fumigant through the seed. Program **DUCT** allows for three different types of treatment:- aeration, recirculating fumigation and flow-through fumigation. For each type of treatment there is a different way of specifying the treatment rate:-

Aeration Systems: Specific Air Flow Rate, Q_s As seed-stores become taller, it is necessary to increase the upward air velocity to ensure that the time for the *air* to traverse the height of the store, t_{air}, s, is maintained at about the same value.

This adjustment can be made *automatically*, regardless of store geometry, if the treatment rate is specified using a *specific* air flow rate, Q_s, ℓ/s-tonne. Q_s is called a *specific* flow rate because it is the flow rate *per mass of seed.* If we take the bulk density of the seed as ρ_g, kg/m^3, the mean height in the store as H_{seed}, m, and the floor area of the store served by the duct as A_{served}, m^2, then we can readily show that the air velocity in the vertical direction, $v_{vertical}$, m/s, is:

$$v_{vertical} = 1 \times 10^{-6} \times \rho_g \, H_{seed} \, Q_s, \tag{2}$$

and the time for the air to traverse (pass through) the height of the store, t_{air}, sec, is

$$t_{air} = \frac{1 \times 10^6}{\rho_g \, Q_s}. \tag{3}$$

Consequently, when we define the treatment rate using a *specific* air flow rate, this automatically ensures that:

- the vertical velocity, $v_{vertical}$, is proportional to the seed height (equation 2),
- all geometric factors (floor area and height) cancel out leaving the time for the *air* to traverse the height of the store, t_{air}, dependent only on the specific air flow rate, Q_s, and the bulk seed density, ρ_g (equation 3), and as ρ_g is roughly constant,
- the air traverse time, t_{air}, *is determined by* the specific air flow rate.

Note that there is a difference between the air traverse time and the time for a *cooling front* to traverse the seed. The traverse time for a cooling front is much greater than the air traverse time because it takes a large volume of air to cool a little seed. The cooling front traverse time depends on a number of factors including the air traverse time, the seed type, the seed moisture content and the initial seed temperature.

As shown in Part 2 of the SGRL Aeration Manual (Wilson, in press), conservative design temperature and moisture conditions can be chosen that allow selection of a *design* specific air flow rate value, $Q_{s,\ design}$, that ensures an acceptable *maximum* aeration cooling time, $t_{cooling}$, under worst case conditions. For example, for aeration of wheat in cooler parts of Australia, we aim for a maximum cooling time, $t_{cooling}$, of 5 weeks and recommend $Q_{s,\ design}$ values of 0.95 ℓ/s-tonne for horizontal stores and 0.6 ℓ/s-tonne for vertical stores.

Recirculating Fumigation Systems: Air-Change Time, H_r For recirculating fumigation systems, program **DUCT** specifies the fumigation treatment rate by the number of hours taken to recirculate the air in the store, H_r, hours/air-change.

Flow-Through Fumigation Systems These systems vent low fumigant concentrations through an unsealed seed-store to atmosphere. During this process, fumigant concentrations are cost-effectively maintained at a sufficient concentration over a time that kills all insect phases. The program *automatically* calculates the appropriate treatment rate for you when flow-through fumigation systems are selected.

Recommended Values of Duct Flow Uniformity, r.

The ratio of the height to the width of a store is important because it affects the uniformity of flow through the seed bulk.

The flow tends to be more uniform in tall narrow stores, which we call vertical stores, than it is in wide squat stores, which we call horizontal stores.

To decide whether a store is vertical or horizontal we suggest use of the following rule:

> A *vertical* store has a mean grain depth, H_{grain}, greater than or equal to twice the square root of the total floor area of the store, A_{store}. If the store doesn't satisfy this condition, it is a *horizontal* store.

Algebraically, the store is vertical if:

$$H_{grain} \geq 2\sqrt{A_{store}}, \tag{4}$$

and the store is a horizontal if:

$$H_{grain} < 2\sqrt{A_{store}}. \tag{5}$$

Because the flow tends to be more uniform in vertical stores than it is in horizontal stores, the *duct* flow uniformity, τ, needed to achieve good flow uniformity in the *seed bulk*, depends upon the seed-store type. For:-

- horizontal seed-stores you need high τ values, for example $\tau = 0.9$, to assure uniform seed treatment, and for
- vertical seed-stores you can use lower τ values, for example, $0.5 \leq \tau \leq 0.9$.

  You can have lower values of τ for vertical stores because:-

  - away from the duct, the flow redistributes and becomes more uniform. Consequently, low flow regions at one end of the duct, affect only seed in the region of the duct. Flow redistribution usually occurs within a height about equal to the width of the store.
  - provided the seed treatment rate is determined by a *specific* air flow rate, Q_s, then the vertical velocity is proportional to the height of the store (equation 2). As vertical stores have a greater height than horizontal stores, the vertical velocity in such stores is also higher. Consequently, even if there is a lower flow rate region at one end of the duct, the vertical velocity in that region is still high enough to ensure satisfactory treatment. Clearly, if the vertical store only just satisfies equation 4, then τ should be closer to 0.9 than to 0.5. As the height increases beyond $2\sqrt{A_{store}}$, so τ can be reduced toward 0.5.

τ values in Evaluation Mode In evaluation mode, the program calculates the flow uniformity, τ, achieved by a duct of specified size. Although you can make your own judgements as to whether the τ value is acceptable, the program will also advise you as to whether the τ value satisfies the following recommended ranges:

Table 1: Satisfactory τ Ranges when Evaluating Duct Performance

Store Type	Height Range	Satisfactory τ Range according to Store Geometry
Horizontal	$H_{seed} < 2\sqrt{A_{store}}$	$0.87 \leq \tau \leq 0.93$
Wide Vertical	$2\sqrt{A_{store}} \leq H_{seed} \leq 4\sqrt{A_{store}}$	$-0.2 \frac{H_{seed}}{\sqrt{A_{store}}} + 1.27 \leq \tau \leq 0.93$
Narrow Vertical	$H_{seed} > 4\sqrt{A_{store}}$	$0.5 \leq \tau \leq 0.93$

τ values in Search Mode In Search mode, the program searches to find the duct area that achieves a specified flow uniformity, τ. The τ value must therefore be specified before the program can begin its search. You can:

- specify your own τ value, or
- have the program automatically specify a τ value according to the following:

Table 2: Search τ Values according to Store Geometry

Store Type	Height Range	τ Value used in the Search
Horizontal	$H_{seed} < 2\sqrt{A_{store}}$	0.9
Wide Vertical	$2\sqrt{A_{store}} \leq H_{seed} \leq 4\sqrt{A_{store}}$	$-0.2 \frac{H_{seed}}{\sqrt{A_{store}}} + 1.3$
Narrow Vertical	$H_{seed} > 4\sqrt{A_{store}}$	0.5

How to Allow for Seed Packing

Seed packing causes closure of the spaces between the seeds. This restricts the flow of air through the seed increasing the pressure load on the fan and making it more difficult to treat the seed. Packing of seed occurs over time because of compression caused by the weight of the seed above the duct. Vibration, for example, from passing trains or unbalanced fan motors, also increases packing. Program **DUCT** allows the designer either to ignore seed packing or to specify the % of packing. Allowance for up to 30% packing is recommended where seed is to be stored for lengthy periods.

How to Optimize Duct Design

If a duct is unnecessarily large, it will perform well but it will be expensive. If a duct is too small its performance will not be satisfactory—the fan pressure load will be high, or, there will be a non-uniform flow along the duct causing over-treatment of seed at the fan end, and an insufficient seed treatment at the other end.

A duct designer's most challenging task is to *optimize* the duct size—to find the smallest duct that will give satisfactory flow uniformity and fan pressure load.

To allow you to easily find the optimum duct size, program **DUCT** has a search mode that can perform two types of search:

- it can find the duct size, (that is, duct cross-sectional area) that gives a specified value of flow uniformity, τ, and
- it can find the duct size that gives a specified value of fan pressure load, $\mathcal{F}$.

We will refer to these two searches as the τ-search and $\mathcal{F}$-search, respectively.

Recommended Search Procedure

Search mode must be used correctly to avoid problems. We recommend that you adopt the following procedure:

- Perform a τ-search *first*, thereby obtaining the duct size needed to achieve the specified τ-value. The τ-search will also give values for the fan pressure load occurring with that τ-value, $\mathcal{F}_\tau$, and the minimum possible fan pressure load, $\mathcal{F}_{min}$.
- You *only* need to perform an $\mathcal{F}$-search if $\mathcal{F}_\tau$ is too high—greater than 1500 Pa.

  If $\mathcal{F}_\tau$ is *less* than 1500 Pa your design problem is solved, you have *already* obtained the smallest duct size needed to give the specified flow uniformity, with an acceptable fan pressure load. You do not need to do an $\mathcal{F}$-search.

  If $\mathcal{F}_\tau$ is *greater* than 1500 Pa, you *may* be able to obtain a useful reduction in fan pressure load by changing the duct geometry or making the duct marginally larger. To find out if this is possible, use the program's $\mathcal{F}$-search.

- For the $\mathcal{F}$-search, keep the $\mathcal{F}$ values that you specify, between $\mathcal{F}_\tau$ and $\mathcal{F}_{min}$.

  Reducing $\mathcal{F}$ from $\mathcal{F}_\tau$ towards $\mathcal{F}_{min}$, will make the duct progressively larger. Consequently, you need to balance duct cost, which is determined largely by duct size, against fan capital and running costs, which are determined by $\mathcal{F}$. You will probably need to perform a number of $\mathcal{F}$-searches to allow you to strike this balance.

Effect of Fan Pressure Load, $\mathcal{F}$

The fan pressure load, $\mathcal{F}$:

- determines both the fan running cost, and
- the temperature rise that occurs in the air passing through the fan.

We should therefore ensure that $\mathcal{F}$ is not *unnecessarily* high. Further, for blowing systems:

- the temperature rise through the fan *beneficially* lowers the relative humidity of the air flowing into the seed, thereby reducing the likelihood of the inlet air wetting the seed,
- *but*, it reduces the capacity of the aeration air to cool the seed.

To balance these factors, we recommend that you *try* to keep $\mathcal{F}$ below 1500 Pa. We have obtained the value of 1500 Pa from our own attempts to balance duct size against fan running cost. You may wish to use a different value. We have chosen the value of 1500 Pa because:

- pressure loads below 1500 Pa can readily be met by common efficient centrifugal fans, and
- it gives a temperature rise of less than 2°C. A 2°C temperature rise:
  - provides a useful reduction in relative humidity of the inlet air,
  - with an acceptable loss of cooling capacity.

Factors Influencing an $\mathcal{F}$-search

In performing an $\mathcal{F}$-search, you should keep the following in mind:

1. $\mathcal{F}_{min}$ is sometimes greater than 1500 Pa.

   The minimum fan pressure load, $\mathcal{F}_{min}$, occurs when the duct is very large. Then, the pressure load associated with flow constriction around the duct is minimized and the pressure load is almost totally that due to the depth of the seed.

   In tall vertical aerated stores, the large seed depth makes $\mathcal{F}_{min}$ greater than 1500 Pa. This is the price that sometimes has to be paid for the convenience and better flow distribution achieved by vertical stores.

2. It is *not* possible to reduce $\mathcal{F}$ below $\mathcal{F}_{min}$.

(a) If $\mathcal{F}_{min} \geq 1500$ Pa, the best you can do is to reduce $\mathcal{F}$ to a value somewhat greater (say 100 Pa greater) than $\mathcal{F}_{min}$ (but still above 1500 Pa).

(b) If $\mathcal{F}_{min} < 1500$ Pa, we suggest that you try to reduce $\mathcal{F}$ to about 1500 Pa. It may also be possible to reduce $\mathcal{F}$ below 1500 Pa. If you do, you should judge whether the further reduction is worthwhile by balancing duct cost against fan capital and running costs.

3. $\mathcal{F}$ is influenced by the duct geometry and width.

The fan pressure load is determined by *both* the seed depth and by flow constriction around the duct. If we make the duct larger and wider, this will lessen the flow constriction around the duct and the fan pressure load will therefore be reduced.

Sometimes, cost-effective reductions in $\mathcal{F}$ can be achieved by making the duct only a little larger and hence wider, or, by changing the duct geometry. Some geometries have a greater width for a given duct cross-sectional area. For example, switching from an in-floor rectangular duct to a split in-floor rectangular duct increases the width for the same cross-sectional area. Also, for rectangular ducts, you can obtain a greater width by decreasing the height-to-width ratio of the duct.

However, you may also find that in obtaining reductions in $\mathcal{F}$, the duct becomes unacceptably large. You must therefore exercise your own judgement as to what is reasonable—you need to balance factors such as the temperature rise through the fan and duct capital cost, against fan capital and running costs.

Usually, to keep the duct size and cost reasonable, you will have to accept some flow constriction around the duct. The best fan pressure load you can achieve will therefore be somewhat greater (say around 100 Pa greater) than the minimum fan pressure load, $\mathcal{F}_{min}$.

Note that reducing $\mathcal{F}$ by making the duct larger gives a *more* uniform duct flow.

4. *Don't* perform the $\mathcal{F}$-search first.

Normally, you should vary τ-values between 0.5 and 0.9 (as recommended in the section above titled "Selection of Input Values: Recommended Values of Duct Flow Uniformity, τ). Usually, this 0.5 to 0.9 range of τ-values will *not* cause problems in the program.

However, $\mathcal{F}$-values *vary widely* and it is not possible to prescribe a safe limited range of $\mathcal{F}$-values, as we can for the τ-values. Consequently, if you *don't* use a τ-search first to obtain $\mathcal{F}_\tau$ and $\mathcal{F}_{min}$ and then, during the $\mathcal{F}$-search, keep $\mathcal{F}$ between these values, you can easily choose:

- An impossible $\mathcal{F}$-value that is below $\mathcal{F}_{min}$ (the program will detect this and stop), or
- An $\mathcal{F}$-value, greater than $\mathcal{F}_\tau$, that is so high that it cannot be obtained without the program making the duct very small. This is likely to cause an extremely non-uniform duct flow leading to numerical problems in the program (the program should detect the onset of these problems, warn you of the cause, and then stop).

So starting-off by defining a τ-value is safe, but starting off defining an $\mathcal{F}$-value (when you don't know what $\mathcal{F}$-values are reasonable) can easily lead to problems.

Conclusions

Program **DUCT** provides a number of unique and useful features. Firstly, it makes a predictive method for evaluating duct performance available to anyone having access to an IBM Personal Computer (PC) or PC compatible. Unlike design programs that use velocity-limiting-rules, program **DUCT** predicts duct performance by solving the momentum equation governing flow along seed-store ducts. It also evaluates duct performance by calculating the fan pressure load, $\mathcal{F}$, and a new performance index, the flow uniformity, τ, that is defined in this paper.

Secondly, program **DUCT** has two modes of operation, an *evaluation mode* that predicts the performance of a specified duct, and a *search mode* in which the program searches to find the duct size needed for a particular application. This unique feature allows users to specify the desired duct performance by selecting a value of duct flow uniformity, τ, or fan pressure load, $\mathcal{F}$. Then the program finds the smallest duct size that achieves that performance. Designers can therefore use search mode to *size ducts.*

Thirdly, having regard to needs for versatility, program **DUCT** can be applied to any duct lay-out and store geometry, and to seven common duct geometries.

This paper:-

- examines some of the factors that influence your selection of the program's input values, including:
  - choice of treatment rate in both aeration and fumigation systems, including, for aeration systems, the relationship between air velocity through the seed and *specific* air flow rate,
  - a method for deciding whether a store is of a vertical or horizontal type on the basis of the ratio of mean seed height, H_{seed}, to the floor-area of the store, A_{store},
  - choice of flow uniformity, τ, values according to store geometry:
    * in evaluation mode, by recommending a satisfactory range of τ values, and
    * in search mode, by specifying a τ value for use in the search, and
  - allowance for seed packing; and
- explains how to use the program's search mode to optimize duct design.

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