The External Aerodynamics of Canine Olfaction

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I. ABSTRACT

Following a review of precedent literature, flow visualization techniques are used to observe external canine olfactory airflows. This reveals the canine nostril as a variable-geometry aerodynamic sampler, being alternately a potential-flow inlet during inspiration and an outlet flow diverter during expiration. Close nostril proximity to a scent source is important. Separate flow pathways are provided for the inspired and expired air by way of nostril flexure. During sniffing, the nostril midlateral slits open to direct the expired air rearward and to the sides, away from the object being scented. If particulates are present on a surface being scented, they are readily disturbed by these expired jets and can be subsequently inspired.

These and other results are brought to bear upon aerodynamic sampling for purposes of chemosensing, in which a sampler or sniffer acquires the airborne trace signal and presents it to an appropriate detector. Preliminary results from a laboratory-prototype sniffer are given.

II. INTRODUCTION

A. Precedent Literature on the External Aerodynamics of Olfaction

There is abundant literature on olfaction, but little on the external aerodynamics thereof. Some initial insight was gained from rabbits (Glebovskii and Marevskaya, 1968), where nostril flare

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was seen accompanying inspiration, lowering the nasal passage resistance to airflow. However, resistance rose again sharply with expiration, when the nostril flare relaxed. The first known data on the external aerodynamics of olfaction were obtained by Bojsen-Møller and Fahrenkrug (1971), who observed expired airflows through moisture condensation on a cold "Zwaardemaker mirror." This showed that the expired streams are directed laterally and downward from the nostrils in the rat and rabbit. Studies of canine nostrils reveal that they also flare during inspiration (Syrotuck, 1972), and that the sniffing pattern of dogs depends upon the scent concentration: "short sniffs" being the norm and "long sniffs" occurring in the case of weak or inaccessible scents (Zuschneid, 1973).

However, despite this background, there exists little or no literature on the external aerodynamics of olfaction for canines or, for that matter, any species except humans (Haselton and Sperandio, 1988). Thus aerodynamic sampling – a key factor in the extraordinary olfactory acuity of canines– remains virtually unexplored.

We have attempted to fill this gap with a series of live canine experiments described in Section III of this chapter.

B. Precedent Literature on Aerodynamic Sampling Technology

The state of understanding of aerodynamic sampling technology, e.g. for traces of explosives, drugs, and contraband, is likewise very rudimentary. Airborne samplers for particles and air pollutants (impactors, cyclones, etc., e.g. Liu and Pui, 1986) are highly developed, following decades of environmental funding, but that is a stationary approach that is inappropriate for present purposes. A search of the technical and patent literature for "sniffers" yields mostly leak-detection equipment with long hoses and hand-held, pointed tips (e.g. Jackson et al., 1998). This approach is intended for the detection of leaking gases such as helium. It does not address standoff distance, required airflow rate, deposition loss in the transport line, or the need to cover large areas in limited time. In short, any sort of mechanical sniffer that mimics a dog's nose appears entirely missing from the literature.

There is, however, important precedent material in the industrial ventilation literature, e.g. Baturin (1971), Goodfellow and Tähti (2001), Heinsohn (1991), and Heinsohn and Cimbala (2002). Aerodynamic inlets are used in local exhaust hoods to capture welding fumes, cooking effluents, and the like. The "reach" of an inlet is defined as the upwind region from which all the air ultimately enters the inlet, while "capture velocity" refers to the airspeed in front of a hood inlet required to overcome a crosswind and thus capture airborne particulates (Heinsohn and Cimbala, 2002).

While such industrial inlets are large and have very high airflow rates compared to what is considered here as a "sniffer," nonetheless there are several common characteristics. For example, a strong distinction is made between the limited reach of an inlet and the much-stronger "throw" of a blowing airjet, even when the volume flux of air is the same for both (Heinsohn and Cimbala, 2002). Thus, close proximity of an exhaust hood to an airborne contamination source is of recognized importance. Further, the idealization of potential flow theory is known in the precedent literature as an essential means of calculating the expected performance of a specific inlet configuration. Finally, the effect of crosswind interference on inlet performance has at least been considered (e.g. Baturin, 1971), if somewhat crudely.

What is desired here, however, is something much smaller and more mobile, for field use as the aerodynamic sampling "front-end" of a chemosensory apparatus. After covering what we learned from dogs, our goal is thus to define the requirements and parameters of sniffer function for such purposes, and to suggest some simple solutions that can meet these demands.

III. CANINE OLFACTION EXPERIMENTS

Lacking much original technology for mobile indoor/outdoor airborne chemical trace sampling, we turned to the outstanding evolutionary example set by canines. In studying the external aerodynamics of canine scenting, we hope to learn principles that underlie the appropriate design of any mimicking device.

A series of live canine experiments was conducted following procedures approved by the Penn State Institutional Animal Care and Use Committee, and using non-intrusive airflow visualization (Merzkirch, 1984). High-speed schlieren videography of thermal air currents (Settles, 2001), light scattering by airborne particles, and direct imaging of nostril motion have been applied in order to achieve a better understanding of the external aerodynamics of canine olfaction.

We studied both pet animals and trained detection dogs ranging from 1-5 years old, including a female Golden Retriever, a male Yellow Labrador Retriever, a female German Shepherd, a male Airedale, a female Malinois (trained for explosive detection), and a male Doberman Pinscher (trained for firearms and drug detection). Canine nares airflows were observed in both open-air scenting and scenting near a ground plane, with emphasis on the latter. A variety of scent sources of a few mm in size was used, ranging from food to neutral objects and including TNT and marijuana scents for the trained animals. In the majority of experiments, the dogs were encouraged to investigate scent sources placed at the center of the camera field-of-view upon a ground plane. Edible treats were used first to train the dogs in this routine. Later, inedible and unusual scent sources were used to encourage investigative behavior. In the special case of the trained dogs (whose handlers were present), the drug and explosive scents were randomly used on occasion, along with other scent sources, to determine whether they elicited any distinctive olfactory behavior. (No such distinction was observed.) In some cases the animal was trained to place its head in a headrest in order to fix the nostril location for the camera, whereupon an airborne scent was presented to it.

Initial observations were made with a sensitive schlieren optical system (Settles, 2001, Sec. 4.1.3) that revealed thermal variations in the olfactory airflows without distracting the animals. Warm or cold scent sources thermally tagged the scent-laden air in these experiments. Schlieren video records at up to 1000 frames/second revealed the following: During panting respiration a large turbulent jet is expired from the mouth, obscuring any scent-bearing air currents in the vicinity. The dog must therefore normally stop panting in order to sniff. Ordinary or short sniffs occurred at a regular frequency of 3-5 Hz, with each sniff cycle being composed of an inspiratory and an expiratory phase.

Inspired air enters the canine nares from a distance of up to 10 cm or more from the scent source, though the animal narrows this distance to essentially zero if allowed. The nature of the nostril inlet airflow is inherently omni-directional; a potential sink flow in which the velocity varies inversely with some power of the radial distance. Thus the detailed spatial distribution of a scent source can only be discerned when the nostril is brought into very close proximity with it. We believe such behavior is an evolutionary adaptation of canines, who depend upon discerning detailed olfactory "messages" to a much greater extent than humans (Thomas, 1993).

To further illustrate this, sample potential-flow calculations were done of the airflow into a symmetric bulbous nares-like inlet at various standoff distances from a ground plane (as simulated by opposed source-sink doublets of opposite sign). In Fig. 1a, streamlines and lines of constant velocity potential are shown for one such case, with an auxiliary plot on the left showing the behavior of the centerline airspeed. Compared to a reference location (Yr) deep within the inlet, the relative airspeed at half this distance to the ground plane falls to about 10%.

This illustrates that the “reach” of such an inlet is extremely limited. Moreover, our flow visualization experiments show that olfactory inspiration at large standoff distances is readily disrupted by crossflows due to ambient wind motion. However, in Fig. 1b the standoff distance between inlet and ground plane is halved. Now more of the inspired airflow sweeps the local surface area directly beneath the inlet, and surface scents are diluted with a smaller volume flux of extraneous air from the surroundings.

Note that Fig. 1 is not meant to represent canine olfaction exactly, but only in principle. The 2-D computation and the lack of a wall viscous constraint in potential flow, among other factors, fail to model reality perfectly. Nonetheless, as noted earlier, relatively-simple potential flow calculations like this are quite valuable in studying inlet performance. Heinsohn and Cimbala, (2002) cover the topic in detail.

Expiration, on the other hand, is capable of being vectored by the geometry of the nostril, and can have many times the “reach” of a potential-flow inlet. In all cases we observed turbulent expired air jets directed to the sides of the dog’s nose and downward, as in the case of rats and rabbits observed previously. A schlieren image of our 1½-year-old Golden Retriever, Bailey, in profile illustrates the downward component of the expired airflow in Fig. 2.

The volume flux of expired air, estimated from the flow visualization results, is about 30 ml/s per nostril. This yields an expired-jet Reynolds number of roughly 260: high enough to expect turbulent flow. Indeed a very short region of laminar flow, if any, is followed by rapid transition to turbulence in the expired jets, seen clearly in Fig. 2.

The capacity for variable geometry is inherent in the anatomy of the canine external nares (Evans, 1993), shown in Fig. 3. The canine nostrils are more than just simple orifices leading to the inner nose. The bulbous *alar fold* obstructs the nasal vestibule, so air must flow around it. Our simultaneous direct nostril videography and schlieren imaging revealed that, during inspiration, nostril dilation allows a pathway to open above the alar fold, which we refer to as the “upper orifice.” However, during the expiratory phase of olfaction, this upper pathway closes and the nostril “wings” (*nasal ala*) flare outward and upward, thus opening the mid-lateral slits (*nasal sulcae*) which lie directly beneath them. The location and geometry of the mid-lateral slit with respect to the alar fold is therefore responsible for diverting the expired airflow laterally and downward.

The dorsal nature of the observed inspiratory airflow through the “upper orifice” suggests that it may be channeled upward toward the olfactory epithelium. The epithelium is well inside the dog’s nose (Evans, 1993), lies above the normal respiratory flow region, and is in direct contact with the brain.

This observed variable-geometry, alternating aerodynamic inlet and outlet is a key evolutionary adaptation of the canine nares: It avoids discharging expired air back against a scent source, which would disrupt the inspiratory aerodynamics of olfaction. Instead, it diverts the expired streams away from the scent source. The same slit-nostril anatomy is found in other species (e.g. bears) that depend on olfaction, and is clearly very ancient: a successful adaptation that was naturally selected long ago.

In cases where they were presented with an inaccessible scent source, our canines displayed the markedly different sniff frequency and airflow pattern referred to earlier as a “long sniff” (Zuschneid, 1973). Here the sniff frequency was only 1/3 - 1/2 Hz and the expired jets were directed less ventralaterally than in the case of short sniffs. However, this behavior was never observed during free investigation of a scent source on a ground plane. We thus focus the remaining discussion on the olfactory aerodynamics of normal or “short” sniffing.

While sniffing a scent source on a ground plane, the orientation of the dog's nose is such that the expired air jets are directed to the rear and sides along the ground plane (Fig. 4). The turbulent mixing of these jets entrains the surrounding air, drawing an air current toward the nostrils from perhaps several cm ahead along the ground plane. This extends the aerodynamic "reach" of the inspiratory olfaction phase and helps, in some scenarios, to draw scents forth from concealed locations. It is a form of aerodynamic ejector or inducer (see also Fig. 5a).

Upon approaching a scent source on a ground plane, several of our test animals displayed a behavior that we call "scanning" (Fig. 5b): Instead of pointing the nose directly at the source, the nose was initially lowered to close nares proximity with the ground plane before reaching the source. The dog then moved its nose horizontally toward the scent source, pausing when the nostrils were directly above it, sniffing all the while. Often the nose was scanned past the scent source, allowing the expired air jets to impinge directly upon it. Finally the nose was returned to a position directly above the scent source for few more sniff cycles. This behavior promotes visual as well as olfactory inspection of an object or surface, and allows a local "survey" of spatial scent distribution. It also has the effect of disturbing any fine particles in the vicinity of a scent source, through the impingement of the expired air jets.

In order to explore the interaction of canine olfactory airflows with surface particles, a light-scattering flow visualization technique was employed (Merzkirch, 1984). The ground plane near the scent source was dusted with talcum powder having a median particle size of 2 μm. A spotlight was then directed obliquely across the ground plane toward, but not directly into, the camera lens. With the camera aimed at a dark background, airborne particles became visible by scattered light.

Using this approach, we observed a strong interaction between the expired olfactory airjets and surface particles aft and to the sides of the nostrils (Figs. 4a and 6a). Impinging upon the ground plane, these airjets produce the classical aerodynamic phenomenon of wall jets initiated by starting vortices (Glauert, 1956). While most disturbed particles are blown away, our test animals often inspired some particles that were rendered airborne in this way. Particle inhalation is most prevalent when the dog "scans" past a scent source and returns, but some particles are inspired purely through the interaction of the inspiratory airstream and the particles on the ground plane.

Experiments with various particle sizes revealed that silica particles smaller than about 100 μm can be made airborne by the impingement of the expired airjets. Particle streak velocimetry at the canine nares further yielded an approximate inspired airspeed of 1 m/s. The characteristic time for the expired airjets to travel the typical 0.5 cm distance from nares to ground plane was estimated at 5 milliseconds. Since the expiratory phase of short sniffing lasts some 30 times longer than this, one may assume that the airjet impingement phenomenon shown in Figs. 4 and 6 reaches a quasi-steady state.

These results lead to a new view of the canine nostril as a variable-geometry aerodynamic sampler that functions alternately as a potential-flow sink inlet and an outlet flow diverter. Given the current level of interest in biomimicry (Benyus, 1997), electronic noses, land mine detection (Strada, 1996), and the extraordinary canine olfactory acuity in scenting explosives and drugs, these observations need to be considered in the design of aerodynamic samplers for chemosensing applications.

IV. THE DESIGN OF AN AERODYNAMIC SNIFFER

A. Background

Applied to a sniffer design, these canine results provide a basic framework of rules under which such a sniffer should function. First of all, it is clear that the sniffer inlet must get as close as possible to the scent source (remote sensing of airborne chemical plumes is a different topic not covered here). This is not only because of the limited "reach" of a potential-flow inlet, but also due to the rapid dissipation of an airborne trace signal by ambient air motion. Thus a proper aerodynamic sniffer needs to be able to approach and examine surfaces and terrain, and to provide a certain level of isolation from disruptive air currents (to be discussed later).

The design of the sniffer inlet plays a key role in optimizing its performance. A simple open-ended tube is not optimum, since it draws in air from the rear and sides as well as from the forward direction. From the field of industrial ventilation (Baturin, 1972 and Heinsohn, 1991), it is well known that fitting such an inlet tube with a "collar" or flange limits the inspired airstream to a hemispherical capture zone in front the inlet, and improves the inlet's "reach". Even better, evolution provides the bulbous canine nares with a faired "bellmouth" entrance, which conforms to the natural shape of potential-flow streamlines (as in Fig. 1), avoids flow separation at sharp edges, and thus has an entry loss coefficient only a few percent of that of a sharp-edged, open-ended tube (see Goodfellow and Tähti, 2001).

Next comes the issue of exhaling the inspired airstream after the chemosensing step is finished. Dogs have evolved a complex variable-geometry nostril for this, but here biomimicry breaks down: No animal larger than a microbe has managed to evolve turbomachinery (Vogel, 1994), but mankind has built small, light, quiet fans and blowers to move airstreams. Lacking these, the dog depends upon a bellows action that is complicated and unnecessary to mimic for the purpose of chemosensing. Instead, the inspired airstream should be exhausted elsewhere, after the detection step, via a once-through system.

Further comes the issue of particulates. In sniffing the ground for landmines, for example (Jenkins, et al., 2000, and Settles and Kester, 2001), it is very likely that surface particulates carry adsorbed explosive-related traces that may be a thousand-fold more potent than traces in the surrounding air. Whether or not a dog collects and desorbs these particles during sniffing is an issue of current debate, but our observations of canine sniffing, given earlier, definitely show particles disturbed and rendered airborne by the exhaled nostril airjets. This can certainly be mimicked, and particle collection/desorption is not to be ignored in some realistic chemosensing applications.

The means to disturb surface particles artificially by way of auxiliary airjets attached to a sniffer inlet are relatively straightforward. Additional information on this topic can be found, for example, in Smedley, et al. (1999).

Nevertheless particle collection and desorption may come at a high cost in terms of the time required to disturb surface particles, inhale them, collect them, desorb them, and direct the desorbed vapors to the detector.

The separation of solid-phase particulates from an airstream is a known technology, mentioned earlier in Sec. II.B of this chapter. It nonetheless requires adaptation to the present problem of sniff-sampling for chemosensing. Depending upon airflow rate and other circumstances, a cyclone separator uses centrifugal force to separate the heavy particles from the air, or else an impactor uses the inertia of the particles to collect them at a sharp turn while allowing the air to turn the corner (Liu and Pui, 1986). Particles in the μm range and above can be removed from the sampled air using such devices. Thus the design challenge of integrating particle removal into an aerodynamic sniffer is within the current state-of-the-art. Even if such particles are not to be desorbed and sensed, their removal may still be necessary to avoid clogging the inlet orifices of some chemosensing detectors.

Inside the canine nose and that of other animals (Cheng et al., 1990), the mucous lining serves to trap particulates. This may be the natural way of sampling and chemosensing aerosol-borne trace substances.

B. A Basic Experiment on Aerodynamic Sniffing

Despite what was learned in our canine olfaction experiments, some basic questions still linger about the aerodynamics of sniffing, e.g. what flow rate is required, as a function of distance from a chemical trace source on a perpendicular surface, in order to acquire a detectable signal? Commercial sampler and industrial ventilation technology, reviewed earlier, does not address such questions. In fact, basic data on sniffer performance, as a function of such variables as sniffer-tube diameter, scent source diameter, standoff distance from a ground plane, and lateral displacement, have apparently never been obtained previously.

A basic experiment was thus designed to investigate the aerodynamic phenomena and performance of sniffing (Fig. 7). A stable thermal layer on a horizontal plane was used as a "scent" source according to the principle of Reynolds Analogy between heat and mass transfer (see, e.g. Heinsohn, 1991). The detector was a thermocouple inside a simple sniffer tube.

The quantitative results of this experiment confirm the importance of sniffer proximity to localize an airborne trace source. For example, in steady-flow operation our experimental sniffer achieved a maximum sampled signal level at a 5 cm standoff distance h from the surface being sampled when the flow rate Q through the sampler was about 1.5 liters/second (Fig. 8). However, when h was reduced to 2.5 cm the required flow rate Q dropped by a factor of 5 and a higher maximum signal level was obtained.

Flow patterns produced by the sniffer of Fig. 7 were once again observed by the schlieren optical method. An example schlieren image is shown in Fig. 9a. Here, air in contact with the ground plane is symmetrically drawn into the flanged inlet of the sniffer. (Fig. 9a is inverted for clarity; due to the buoyancy of the warm thermal boundary layer on the ground plane, the experiment was done upside-down.)

In transient sniffer operation a surprising behavior was observed: the sampled signal rose quickly to a "spike" at the sniff onset (Fig. 9b), followed by signal decline due (apparently) to depletion of the available trace-saturated boundary layer on the surface. It was also observed that steady-flow sniffing shows extreme sensitivity to transient disruptive air currents, which destroy the symmetric flow pattern of Fig. 9a and literally "blow the signal away."

These results suggest aerodynamic sampler design criteria for chemosensing and electronic-nose devices. Unfortunately the experiments had to be terminated before measurements could be made at larger standoff distances or with unstably-stratified trace-bearing layers and their resulting thermal plumes, and before the effect of ambient wind could be quantified.

C. Other Considerations in Aerodynamic Sniffer Design

Nonetheless, more can be said regarding design issues of the aerodynamic sampling "front-end" required to mate with a suitable detector for the purpose of chemosensing trace detection. A discussion of two specific topics follows.

Sniffer/detector impedance matching. Detector characteristics play an important role in determining a sniffer design. For example, some chemosensory detectors may allow or even take advantage of a relatively-high air volume flux Q. In this case no pre-concentration step is called for, and high Q also means an extended inlet "reach." Most detectors, however, can accept only a very small airflow input. Mass spectrometers and ion-mobility spectrometers, for example, input only milliliters/minute or less from a total sampled airflow rate that needs to be at least 10^4 to 10^5 times that value for effective aerodynamic sampling, based on Fig. 8. This leads to what we have dubbed, by electrical analogy, the "impedance matching" problem between the high airflows that must be sampled in practice and the miniscule airflows that actually feed the chemosensory trace detection step. If impedance matching is not done at all or is done poorly, most of the available signal is discarded. Since the signal level is a mere trace to begin with in applications like land mine detection (Jenkins et al., 2000) and anti-terrorism (Gowadia and Settles, 2001), detection is likely to fail in such cases.

One solution to the impedance-matching problem is to pre-concentrate the trace material by passing the sampled airflow through an appropriate pre-concentrator, then discarding the main flow and desorbing the pre-concentrated trace material with a separate clean-gas flow matching the input requirements of the detector. This works well for aviation security portals (Settles and McGann, 2001 and Settles, 2000) but may prove too slow for other applications like land mine detection. Fast pre-concentration is thus a fruitful topic for further research.

In some cases, re-sampling from a relatively-high inspired airflow rate Q is needed in order to provide a very-low flow rate to the chemosensing detector. If the originally-inspired airstream is not homogeneous, trace detection can be defeated at this step. Under such circumstances flow mixing vanes or "turbulators" are called for between the sampler inlet and the chemosensor, not unlike the *ethmo-turbinates* inside a dog's nose.

Ambient wind isolation. Finally, it is especially important to provide some aerodynamic isolation for a sniffer that must operate, either outdoors or indoors, under conditions of a cross-breeze. As already noted, both in our experiments with dogs and in our basic sniffer experiments, an open, unshrouded inlet becomes extremely sensitive to crosswind disruption as the standoff distance is increased. A practical compromise thus becomes necessary among standoff distance to accommodate terrain and vegetation (in outdoor applications), suction airflow rate through the sniffer, and effectiveness in a crosswind situation.

Our preliminary experiments have shown some success in shrouding the sniffer inlet using soft brush bristles or a fine-mesh screen in order to reduce the effects of ambient crosswind on sampling efficiency. Such aerodynamic isolators work by producing a lateral pressure drop and thus a resistance to the crossflow, and they have the added advantage of providing a soft rather than a hard contact when the sniffer contacts surfaces under examination.

More work is needed on this topic, however. While no specific studies of the aerodynamic isolation problem are known, there is nonetheless relevant information in the fluid dynamics literature (e.g. Cant et al., 2002).

V. CONCLUSION

Little precedent technology was found for mobile indoor/outdoor airborne chemical trace sampling. By studying the external aerodynamics of canine scenting, we have learned some principles that underlie the appropriate design of a mimicking device. Unable to improve upon the inherently-short range of a potential-flow inlet, evolution has instead given the canine an agile platform with which to bring its aerodynamic sampler into close proximity with a scent source.

Based further on experiments with a laboratory-prototype sniffer, we have attempted to state some guiding principles for aerodynamic sniffer design and practice. This work is preliminary, however, and more needs to be done on such issues as the effects of large sniffer standoff distance, lateral separation between sniffer and trace source, unstable thermal stratification, and aerodynamic crosswind isolation.

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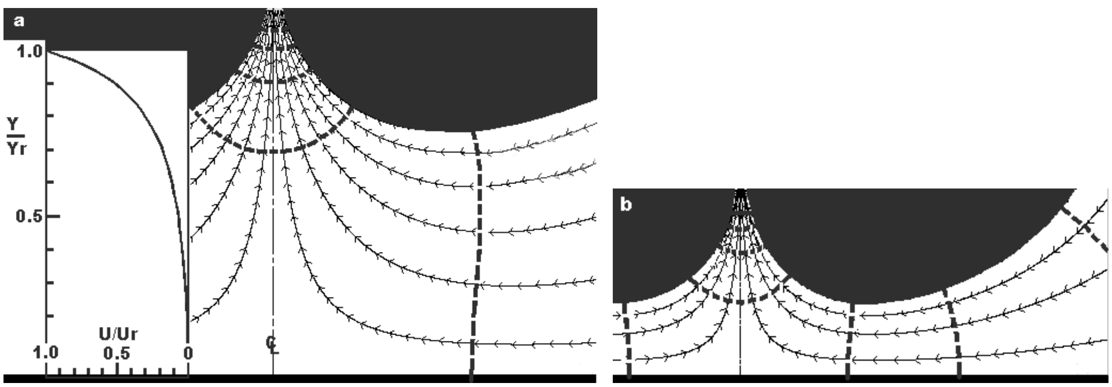


Fig. 1 – Potential-flow air streamlines for simulated canine olfaction with nostril in close proximity to a perpendicular ground plane. The distance from the doublet singularity to the ground plane is halved between Figs. 1a and 1b. Inspired streamlines are arrowed, while lines of constant velocity potential are dashed.

Fig. 2 – Schlieren image showing vectored orientation of expired turbulent canine nostril air jets. Black object is headrest. Scent source is held in forceps.

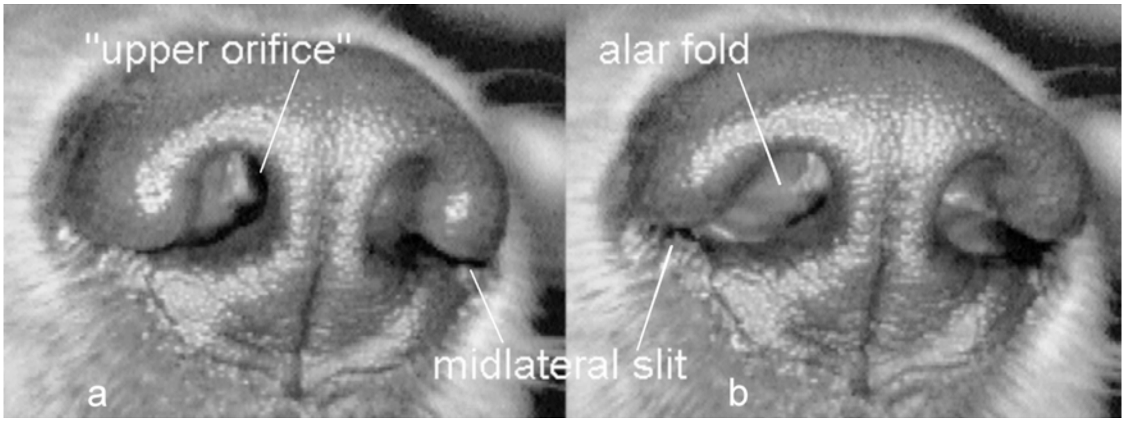


Fig. 3 – The canine external nares during inspiration (a) and expiration (b). The bulbous alar fold is seen as an obstruction just inside the nostril.

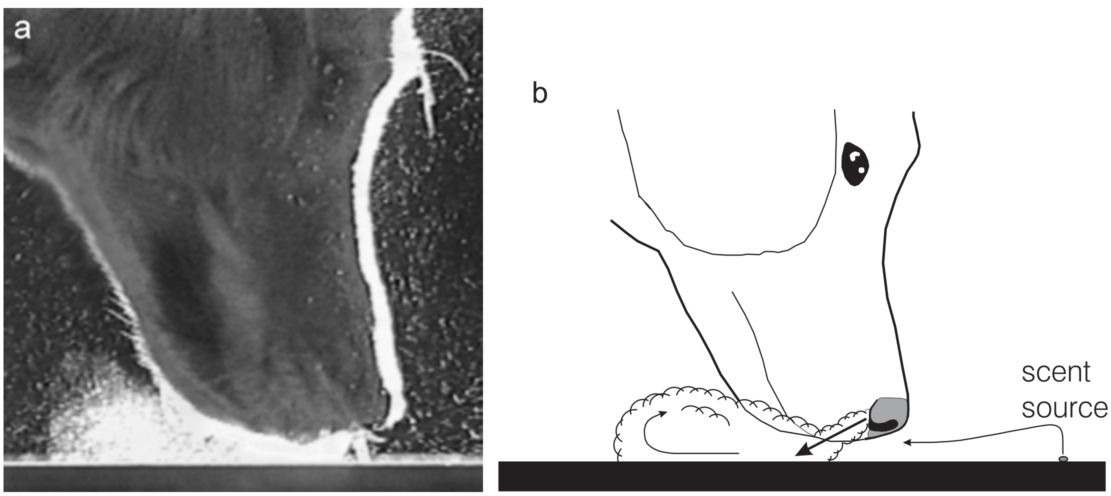


Fig. 4 - Olfaction at a ground plane, side view, visualized using particle light scattering (a). Aerodynamic "inducer" effect due to entrainment by expired air jets (b).

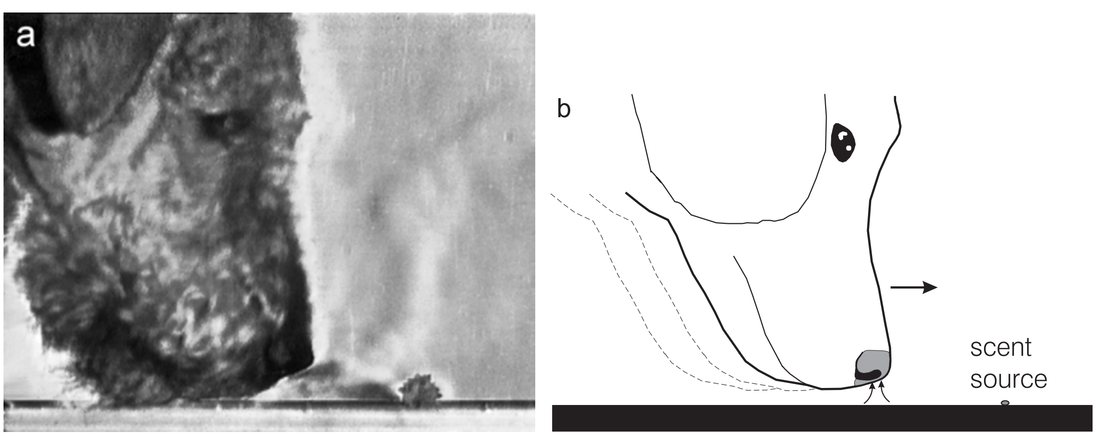


Fig. 5 – (a) Schlieren image showing aerodynamic induction of scent into Airedale's nostrils. Scent source (a small flower) was warmed to make airflow visible. (b) Diagram of olfactory "scanning" of the ground plane.

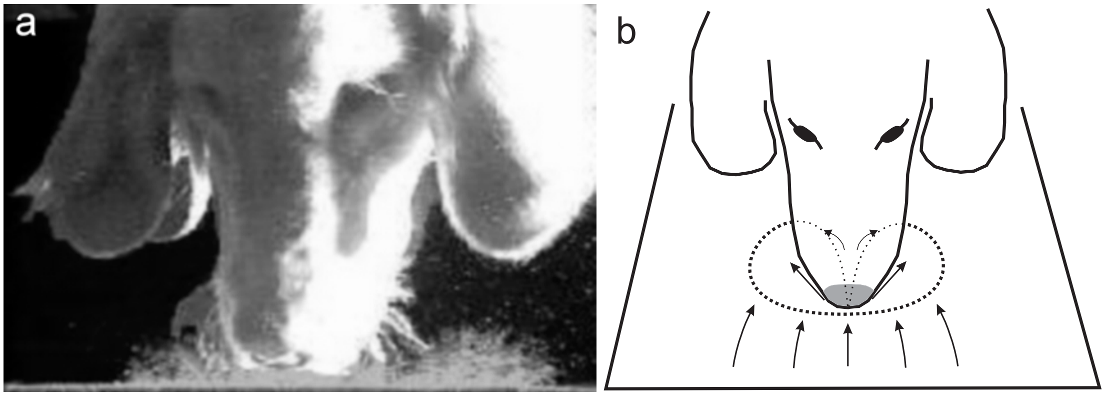


Fig. 6 - Olfaction of a scent source on a ground plane, front view, visualized using particle light scattering (a). Diagram of the pattern of expired-air jet impingement upon the ground plane, showing the directions of entrained air streamlines (b).

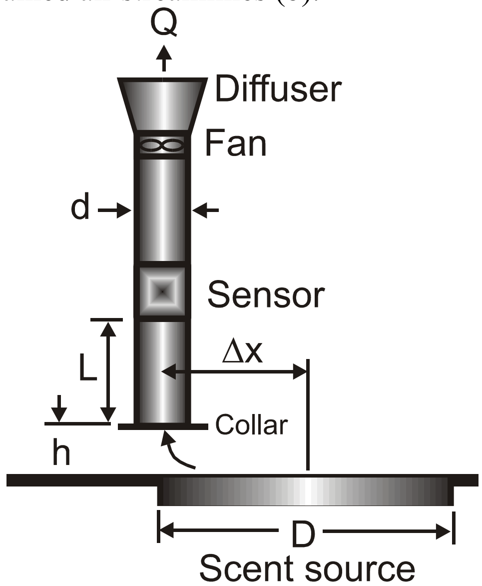


Fig. 7 - Conceptual design of an aerodynamic sniffer (Settles and Kester, 2001). Given a surface contamination zone ("scent source") of diameter D, the sniffer inlet of diameter d is positioned at standoff distance h above the ground plain. A fan draws airflow rate Q through the inlet, part of which is sampled by the sensor. After sampling, the airflow is discarded through a diffuser for pressure recovery. Lateral separation between the sniffer and the scent source is indicated by distance Δx.

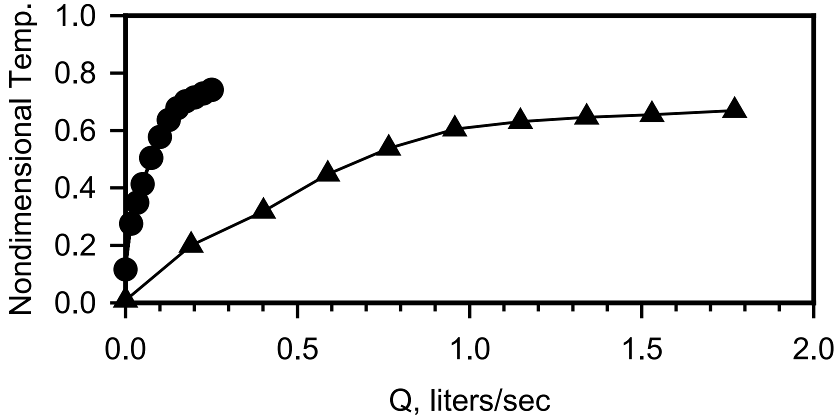
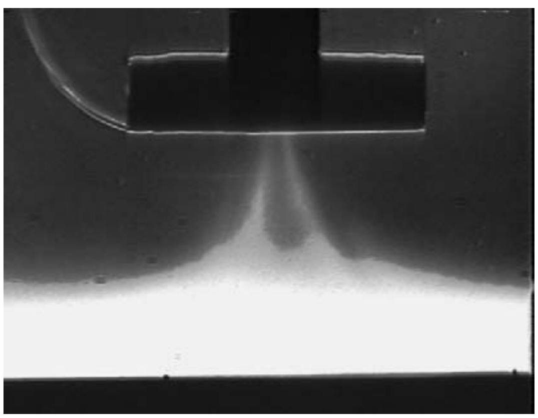


Fig. 8 - Data from the basic sniffer aerodynamics experiment. D= 25 cm, d = 2.5 cm, Δx = 0, λ h= 2.5 cm, σ h = 5 cm.



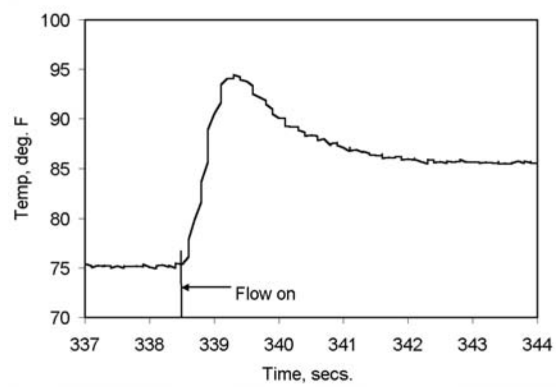


Fig. 9 - a) Schlieren image of stable thermal boundary layer being drawn into sampler inlet during basic experiments on sniffer aerodynamics, b) Detected signal strength as a function of time from beginning of inhale airflow, demonstrating initial spike and signal depletion effect.